POETIC IV
Physics Opportunities at an Electron-Ion Collider
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Low-x Physics at the LHeC

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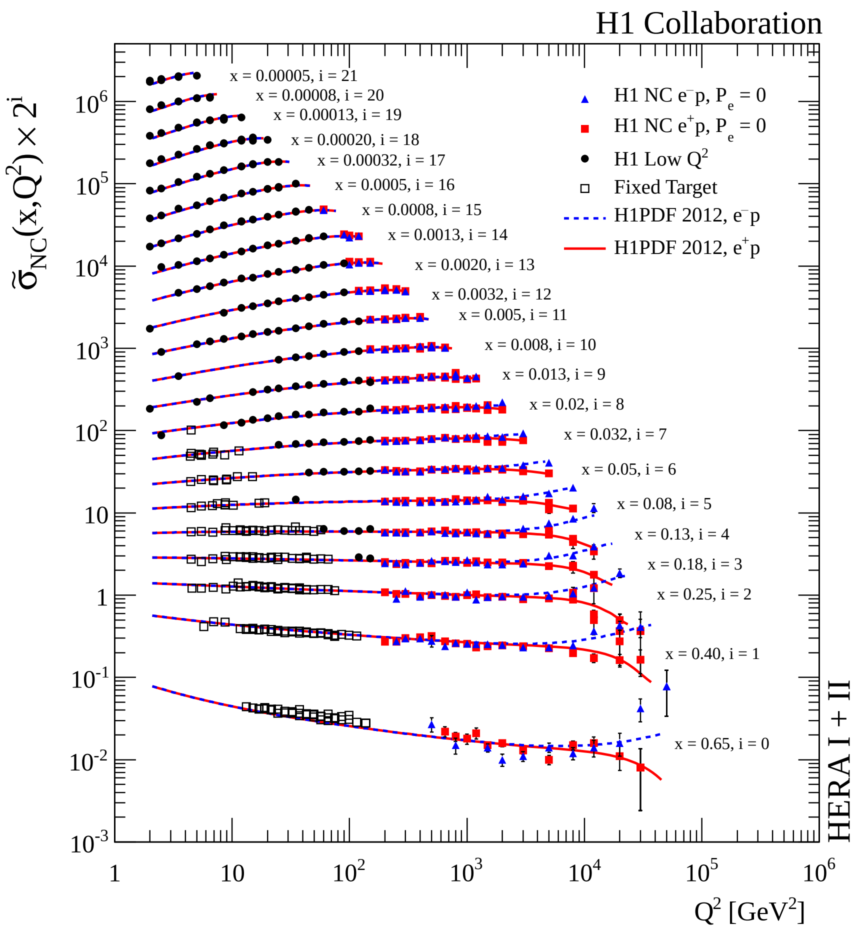
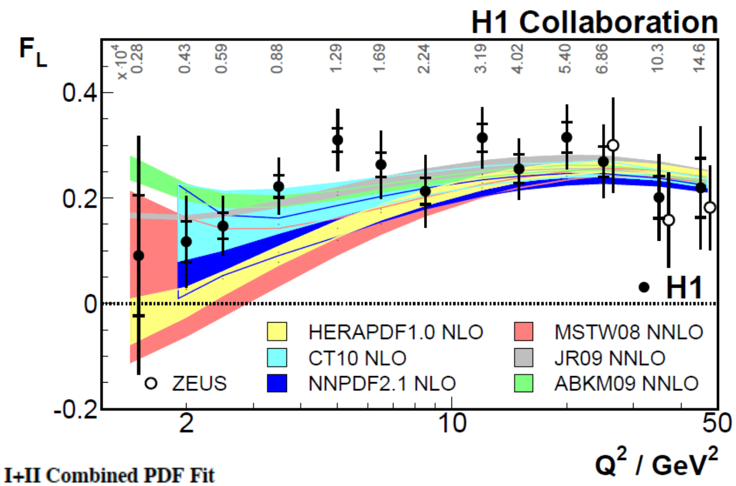
- **Inclusive measurements at low x**
- **Diffraction**

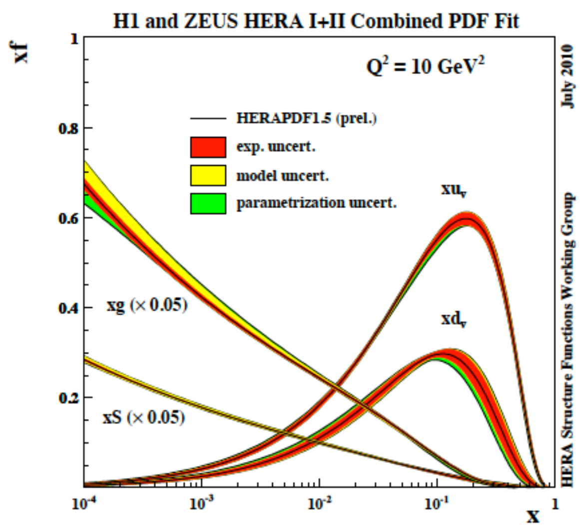
CDR, arXiv:2306.2913, 1211.4831, 1211.5102
http://cern.ch/lhec

Legacy from HERA (1992-2007)

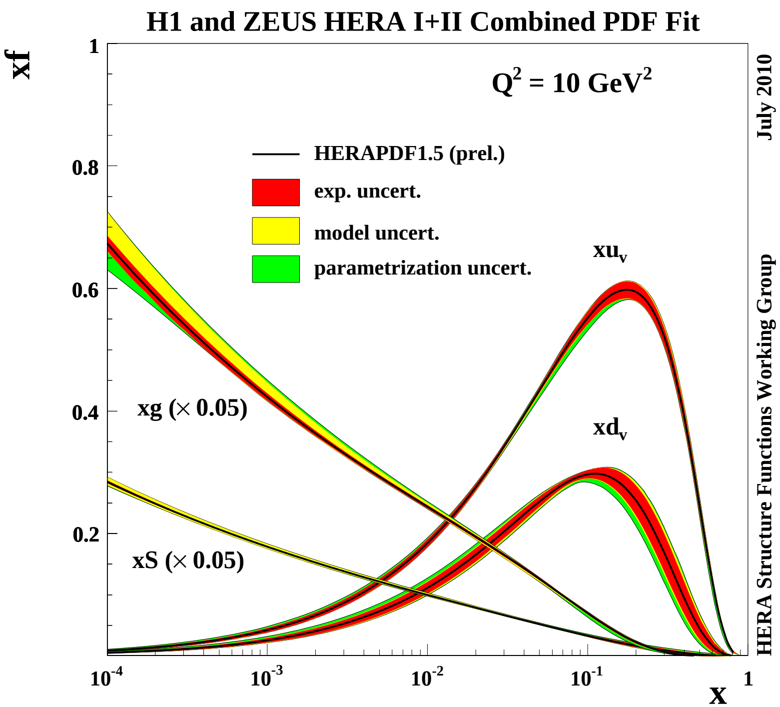
- Proton structure functions in a wide x,Q^2 range; $xg(x) \propto 1/x^{\lambda}$, $\lambda>0$; PDFs
- Large contribution of diffractive proceeses **$\sigma_{diff}/\sigma_{tot}$ ~ 10%**
- Precision tests of QCD with jets, heavy flavours,…
- But: no eA/eD, kinematical reach at small x, luminosity at high x /for searches,







Parton densities at low-x



- Parton densities exhibit a strong rise towards low x and fixed Q^2

→ QCD radiation of partons leads to a large number of gluons (each parton evolves independently- linear evolution $\Delta[xg] \propto xg$)

→ eventually will violate unitarity

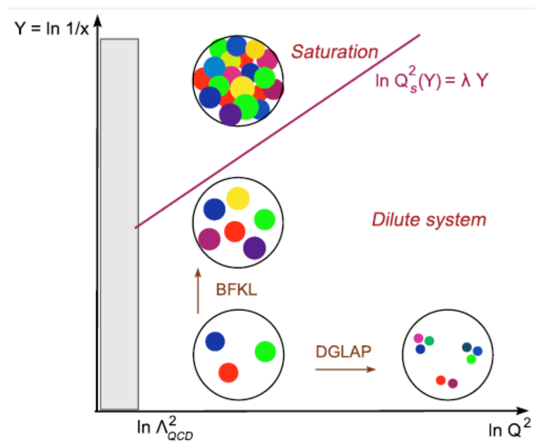
- This independent evolution breaks at high densities (low x/ high A), non-linear evolution must become relevant and parton densities must saturate

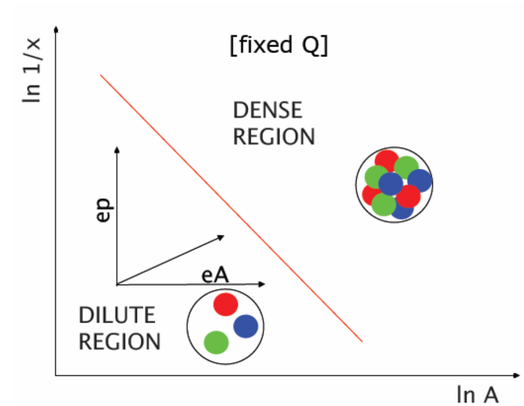
→ recombination ($gg \rightarrow g$) / saturation

LHeC can access very low x, study

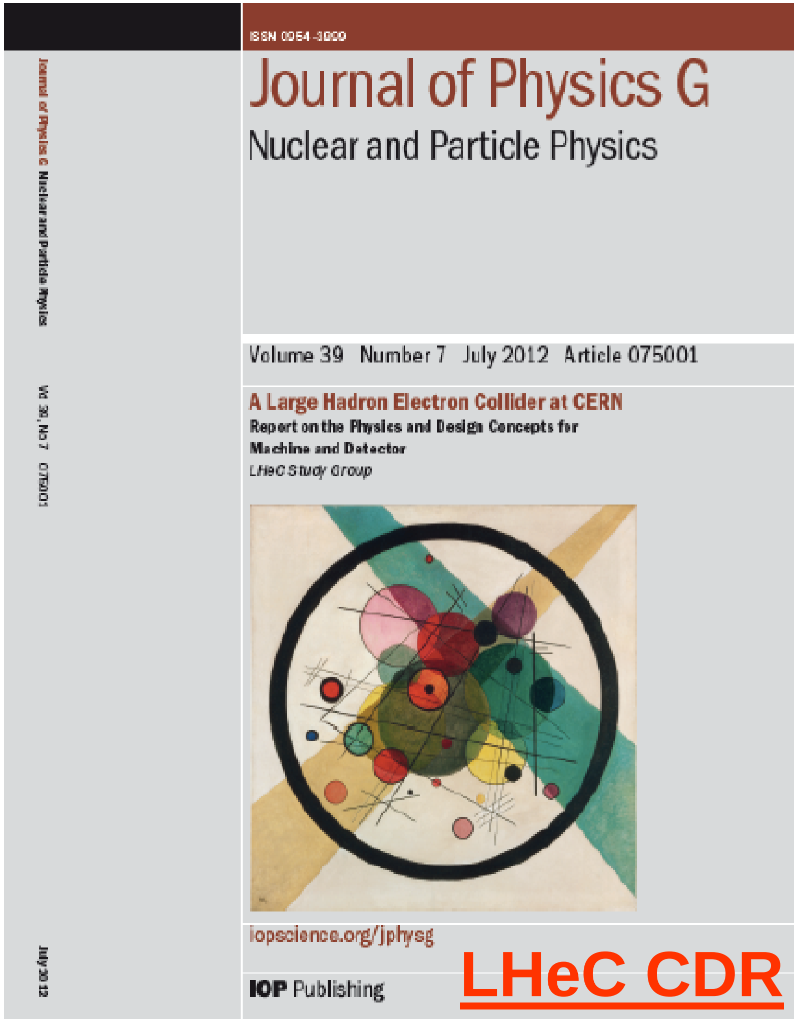
- associated microscopic dynamics

- transition between perturbative and non-perturbative dynamics





LHeC Conceptual Design Report



LHeC CDR

LHeC Study Group

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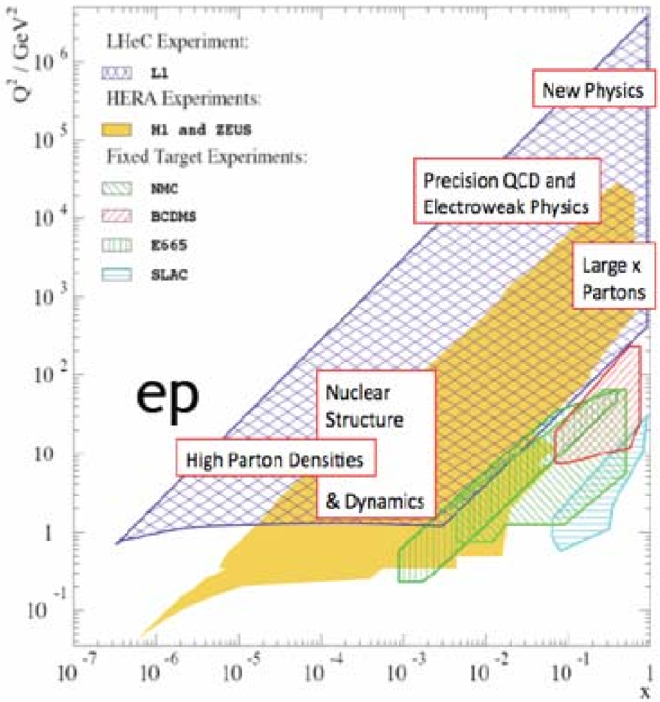
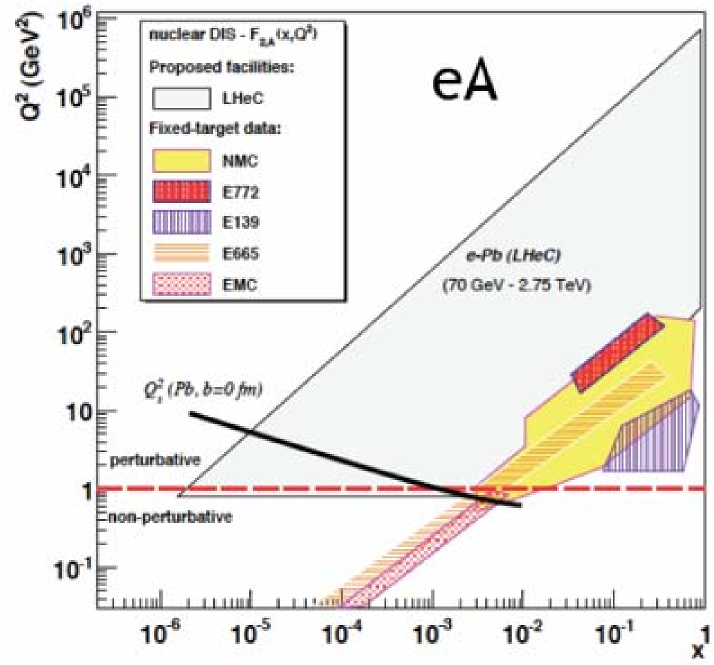
arXiv:2306.2913, 1211.4831, 1211.5102
http://cern.ch/lhec

Physics at LHeC

ep/eA collisions;
$E_e = 60 \div 140$ GeV
$E_p = 7$ TeV
$E_A = 2.75$ TeV/nucl.
$\sqrt{s} \sim 1 \div 2$ TeV

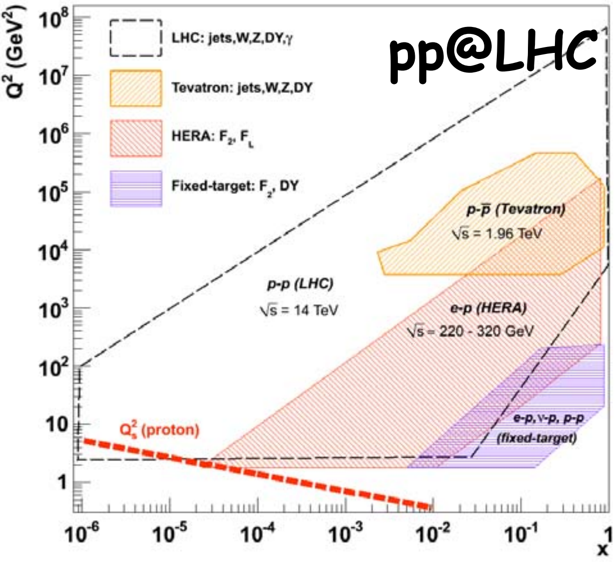


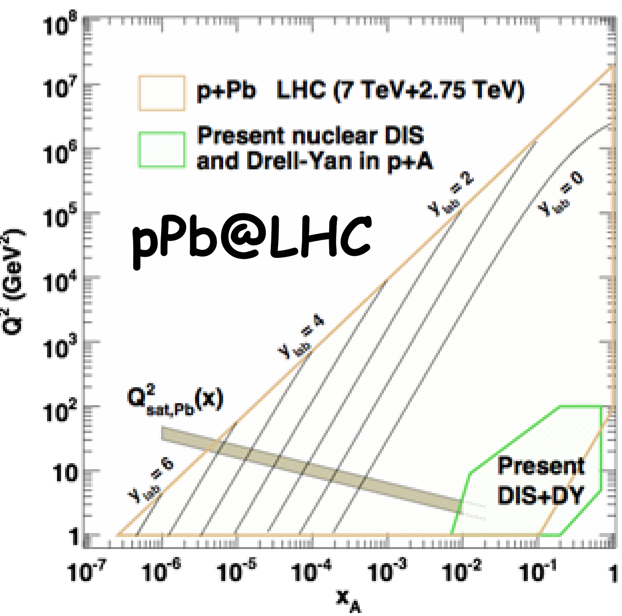


- increase of kinematic range at low x: ep - ×20; eA - ~ 4 orders of magnitude

➔ significant improvement of existing constraints on parton densities

- Establish the existence of physics beyond DGLAP
- Substructure/parton dynamics inside nuclei with implications on QGP search.
- Precision QCD/EW physics
- High-mass frontier (leptoquarks, excited fermions, contact interactions).
- Access (ep and eA) to a qualitatively novel regime of matter predicted by QCD

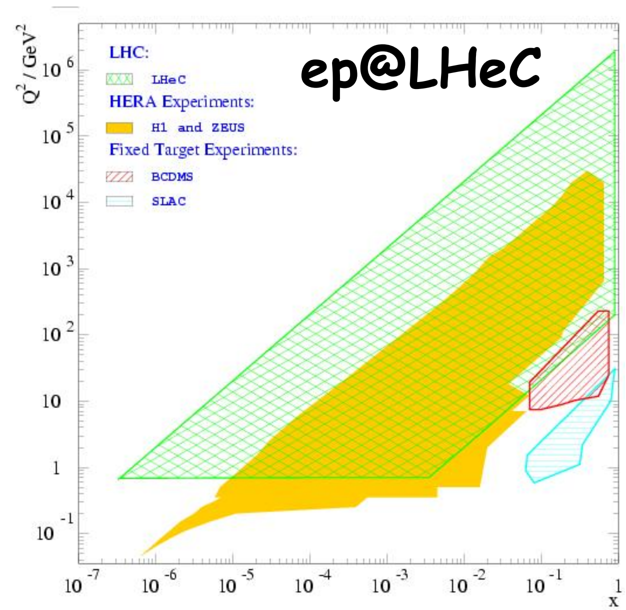


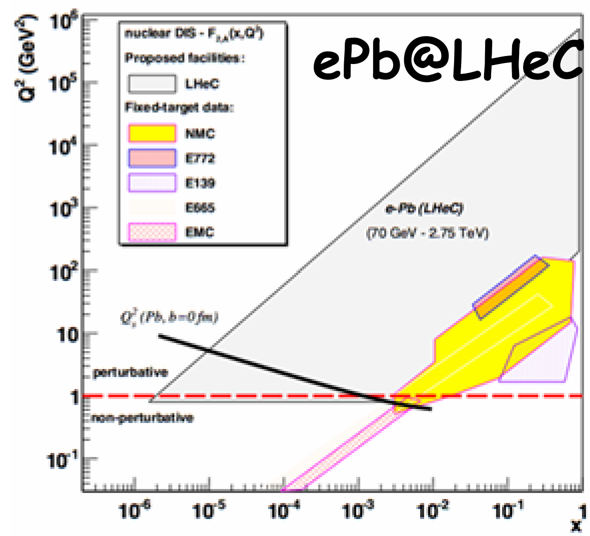


- The LHeC will explore a region overlapping with the LHC

➜ in a cleaner experimental setup

➜ on firmer theoretical ground





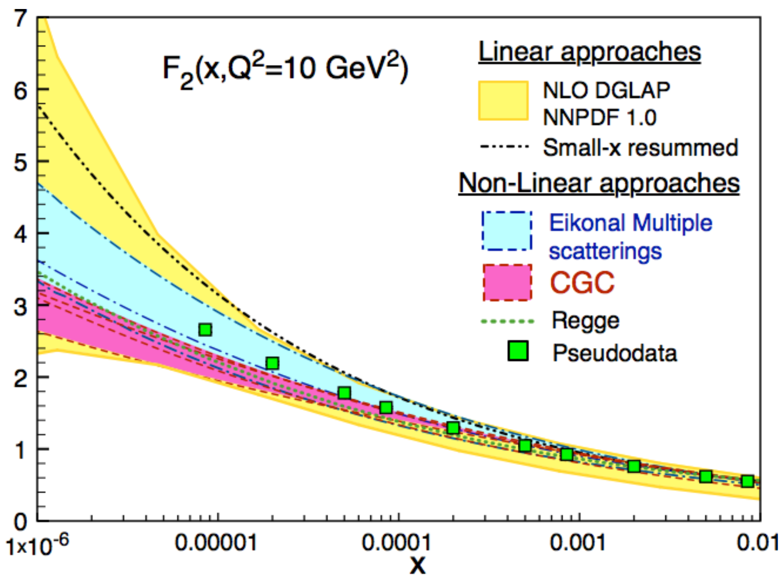
Inclusive measurements: comparison with models

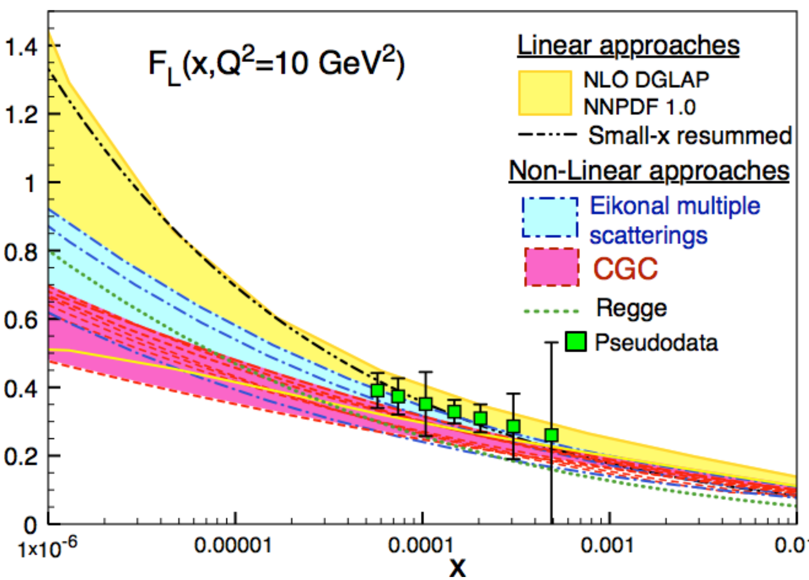
different pQCD-based approaches to describe evolution at low-x

→ DGLAP evolution (fixed order perturbation theory).

→ Resummation schemes: BFKL, CCFM, ABF, CCSS

→ Saturation (CGC, dipole models)





- Models based on linear evolution approaches

  - extrapolation from the NLO DGLAP fit (NNPDF) and the results from a combined DGLAP/BFKL approach, which includes resummation of small-x effects

- Models which include non-linear small-x dynamics

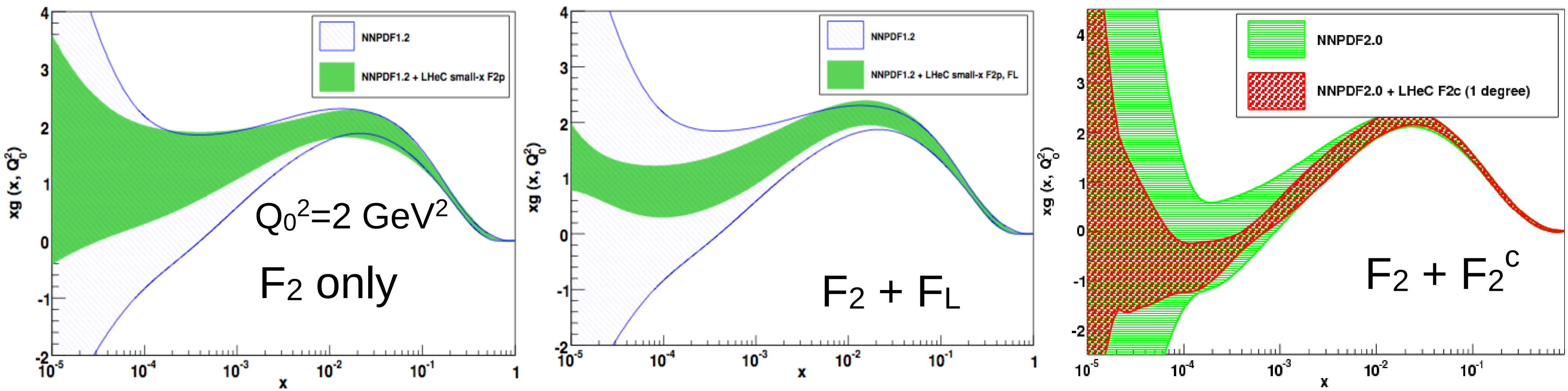
  - dipole models, based on eikonalisation of multiple scatterings with DGLAP evolution and CGC

LHeC F_2 and F_L data can discriminate between models

Constraining Proton PDFs at small x

- uncertainties in predictions due to poorly known parton densities at small x
- LHeC can substantially reduce the uncertainties in global fits (in particular F_L and heavy flavours useful)

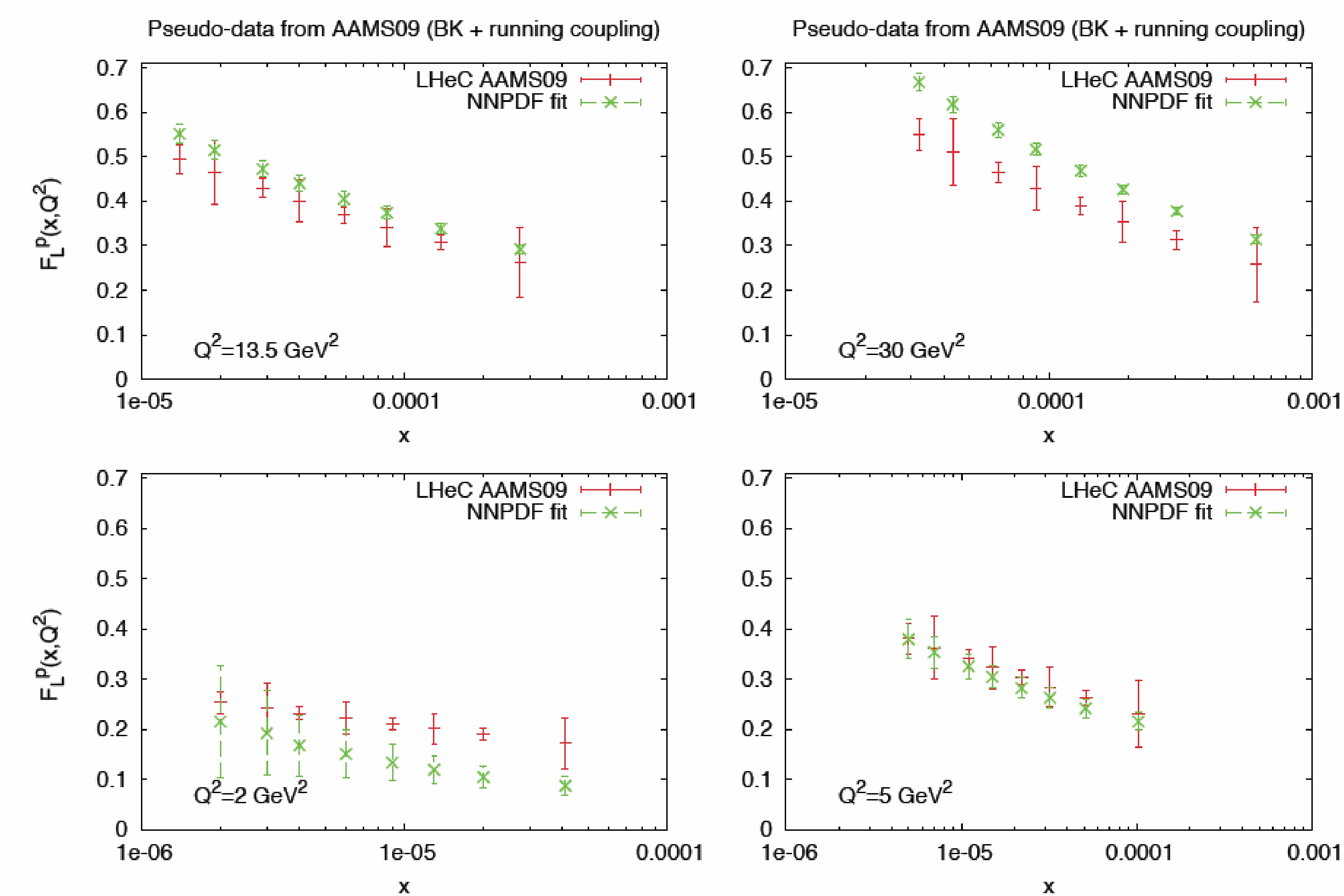
xg(x) in NNPDF DGLAP fit with LHeC pseudodata (which include gluon saturation effects: AAMS09, FS04)



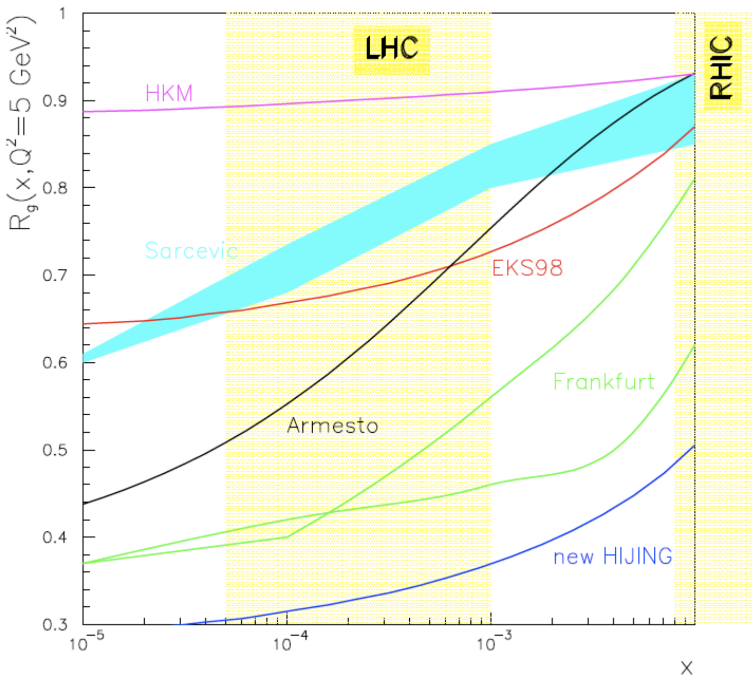
F_L measurements- sensitivity to effects beyond DGLAP

Combined F_2 and F_L measurement is very sensitive probe of novel small-x QCD dynamics

NLO DGLAP cannot simultaneously accommodate LHeC F_2 and F_L data if saturation effects included



Nuclear Parton Densities (nPDFs) at small x

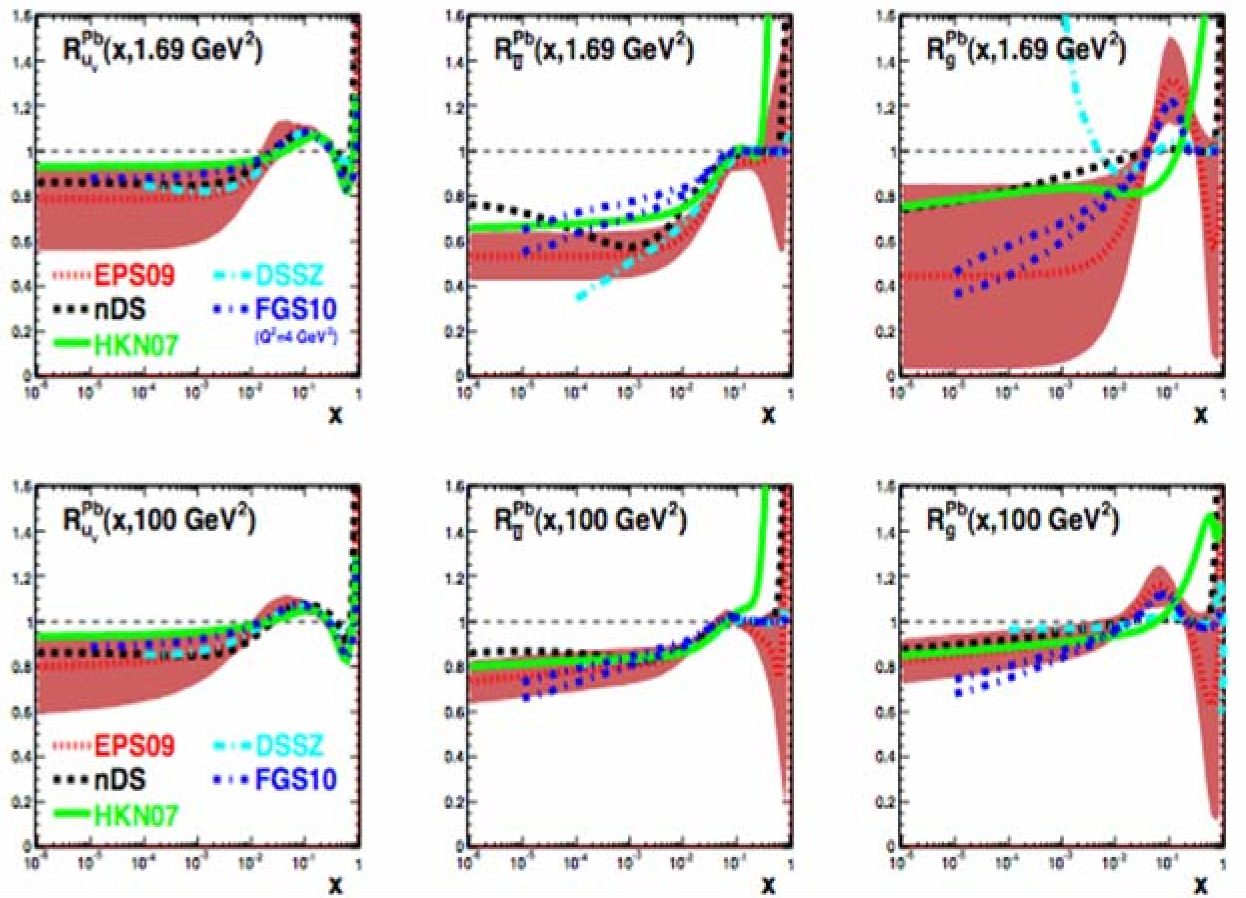


(ratios of gluon distribution functions at Q^2=5 GeV^2)
Yellow Report on Hard Probes, 2004

$$R = \frac{f_{i/A}}{A f_{i/p}}$$

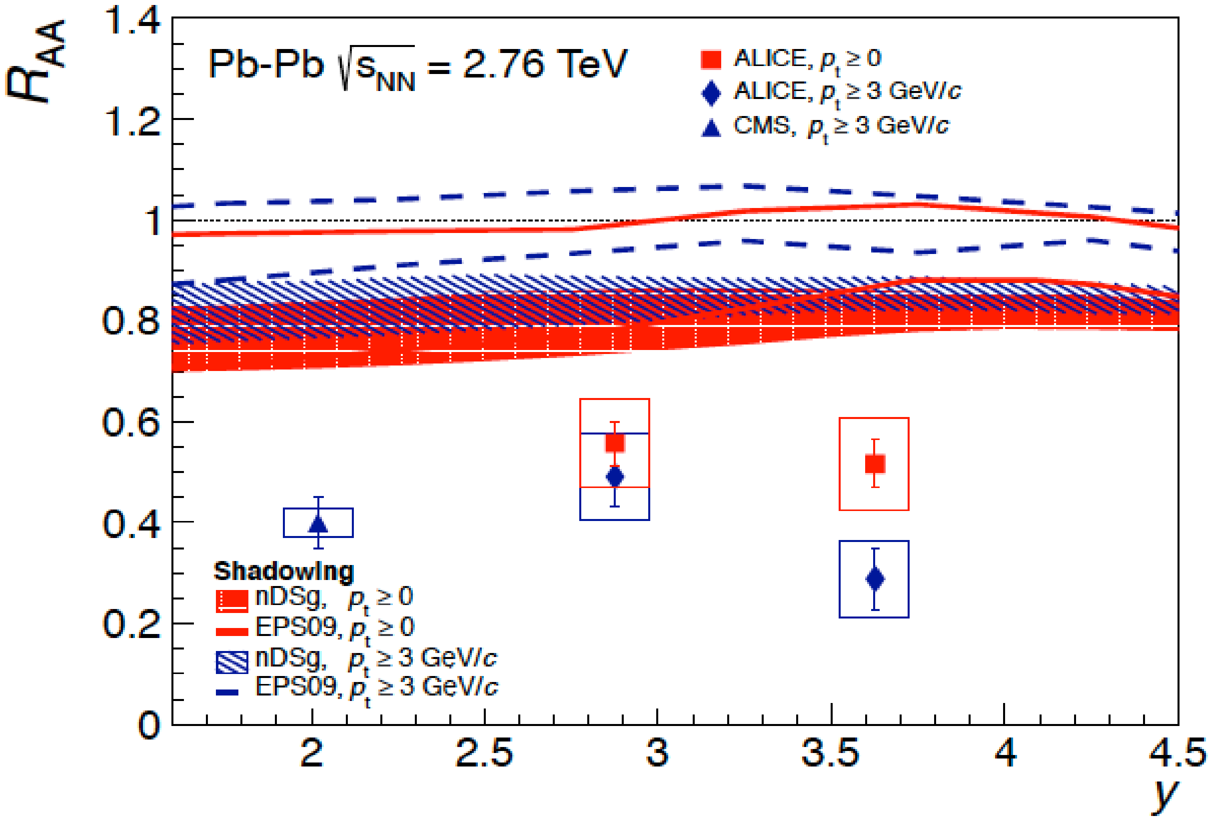
ratio of parton densities in bound proton in Pb to those in free proton

Lack of data → models give very different results for the nuclear glue at small scales and x



Large uncertainties in NLO DGLAP analyses at small scales and x

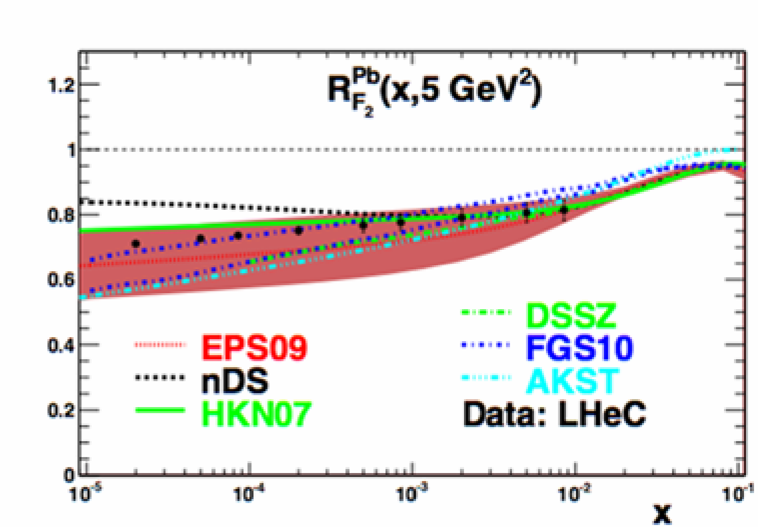
(R - nuclear modification factor)

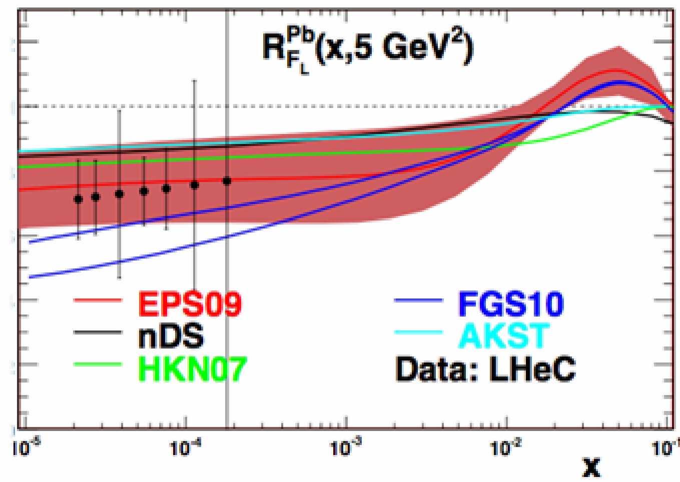


Inclusive J/ψ, 1202.1383

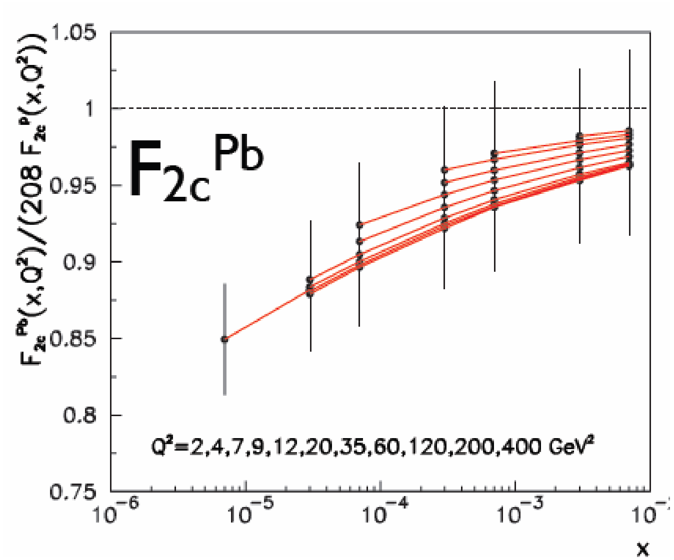
eA at LHeC: impact on nPDFs

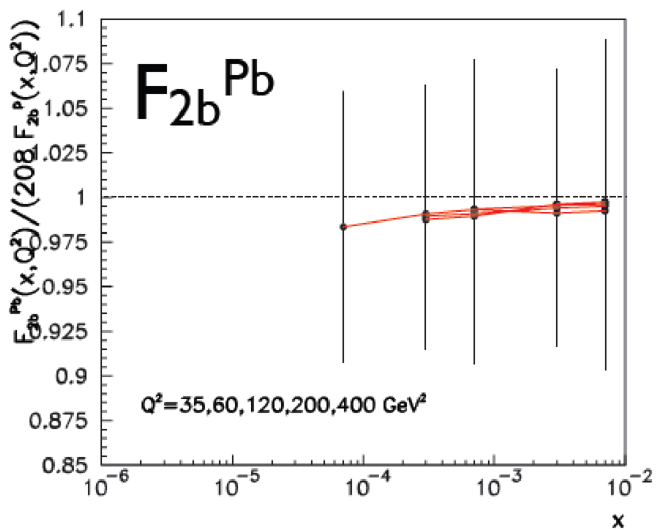
Good precision can be obtained for F_2 and F_L at small x



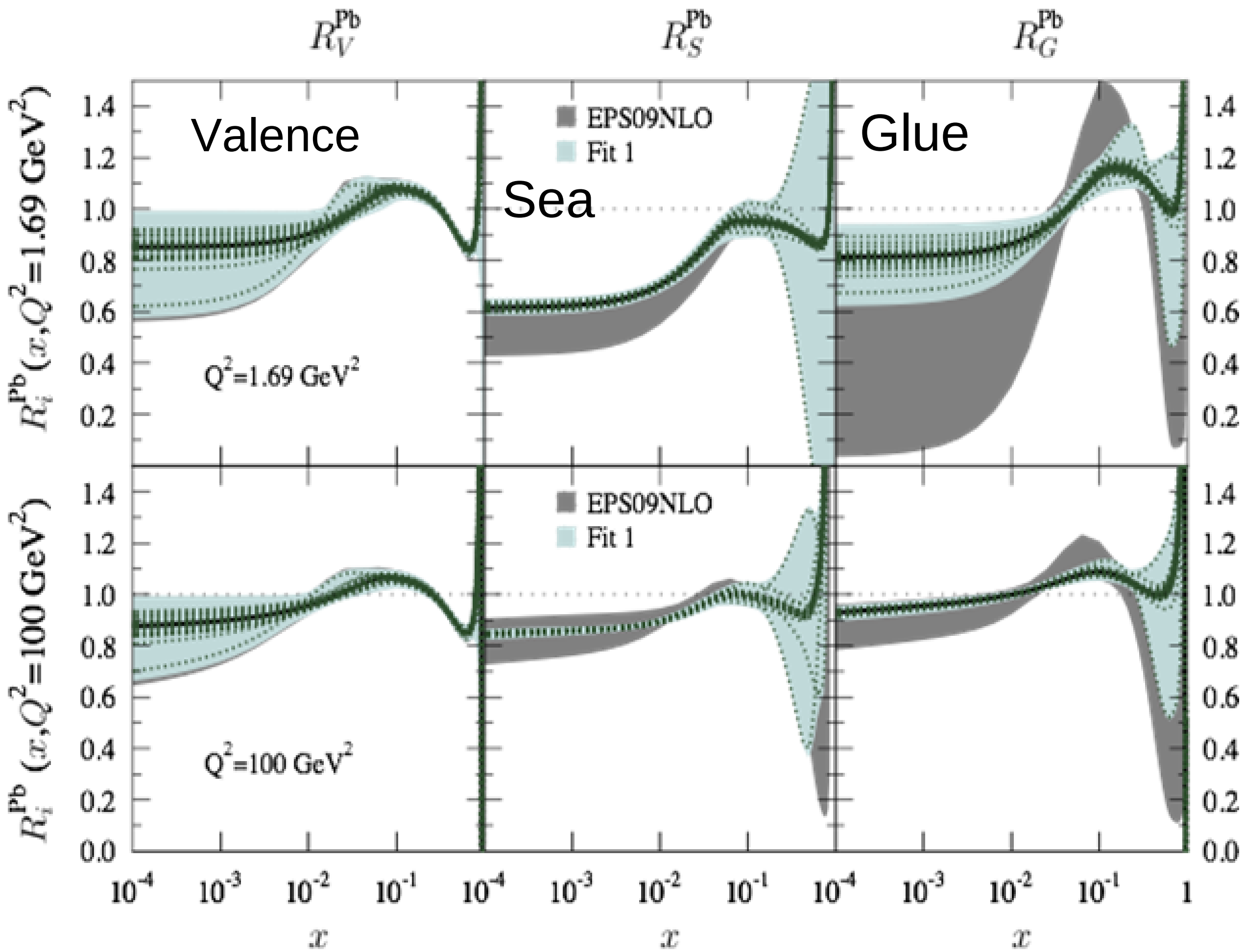


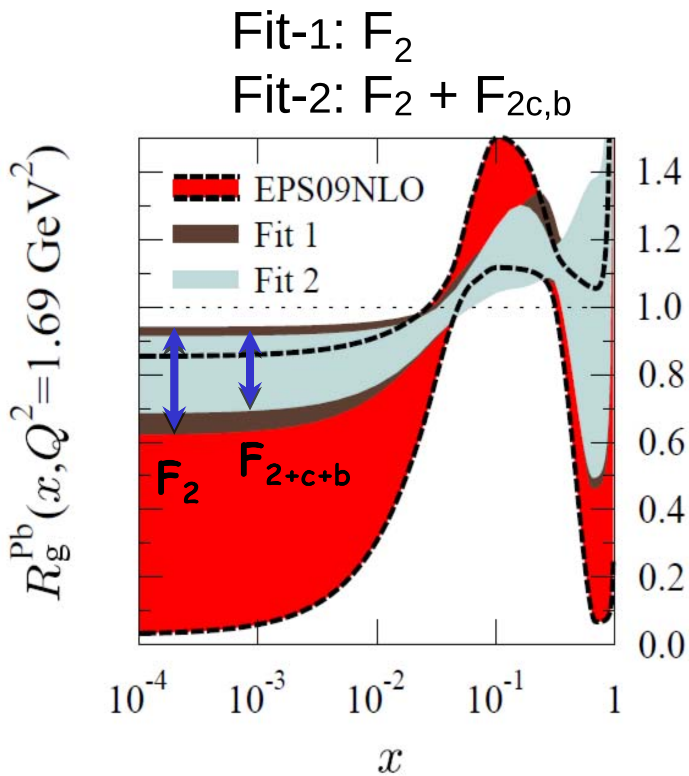
LHeC pseudodata simulation with Glauberized 5-flavour GBW model (N.Armesto)





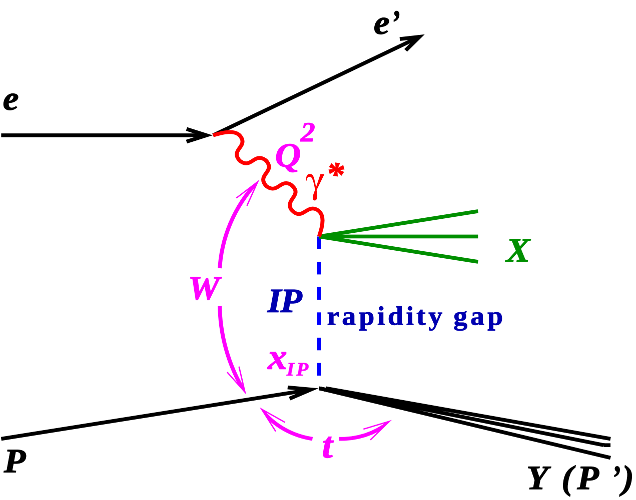
F_2 data substantially reduce the uncertainties on nPDFs in DGLAP analysis;
Additional constraints from charm, beauty and F_L





Diffraction in ep collisions

One of the first HERA surprises: ~10% of DIS events have no activity in proton direction → *diffractive interactions*



$Q^2 = -q^2$	photon virtuality
$x = \frac{Q^2}{2q\cdot p}$	Bjorken scaling variable
$W^2 = (p+q)^2$	$\gamma^* p$ CM energy squared
$t = (p - p_Y)^2$	4-momentum transfer squared
$x_{I\!P} = \frac{q\cdot(p-Y)}{q\cdot p}$	fraction of p momentum transferred to $I\!P$ ($x_{I\!P} \simeq 1 - E_Y/E_p$)
$\beta = \frac{Q^2}{2q\cdot(p-Y)}$	fraction of $I\!P$ momentum carried by struck quark ($x_{I\!P}\beta = x$)
M_X	Inv. mass of system X

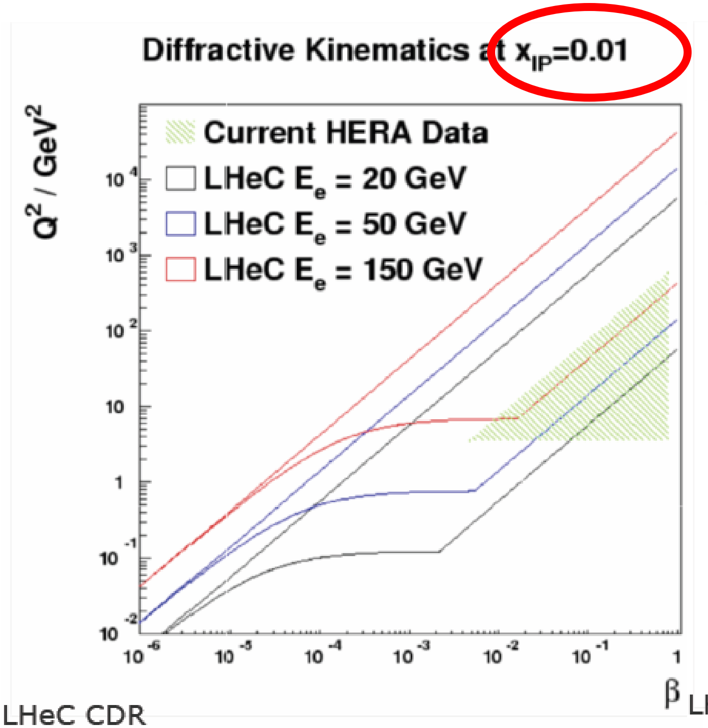
- t-channel exchange of vacuum quantum numbers
- proton survives the collision intact or dissociates to low mass state, $M_Y \sim O(m_p)$
- large rapidity gap
- small t (four-momentum transfer), small x_{IP} (fraction of proton momentum); $M_X \ll W$

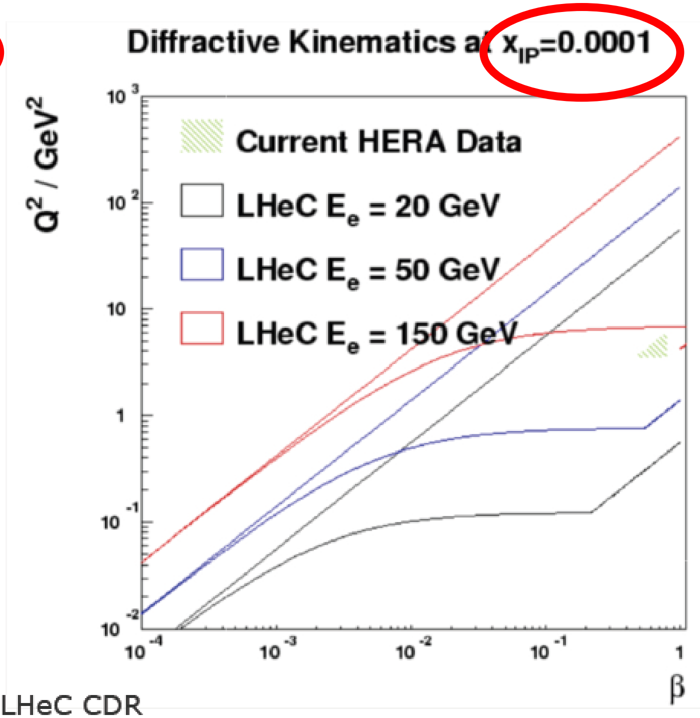
In diffractive DIS, γ^***p→XY** , virtual photon resolves structure of colour singlet exchange
Understanding diffraction in terms of partons
- essential for the predictions of diffractive cross sections (e.g. diffractive Higgs)
- related to non-linear evolution (saturation), underlying event (gap survival), confinement

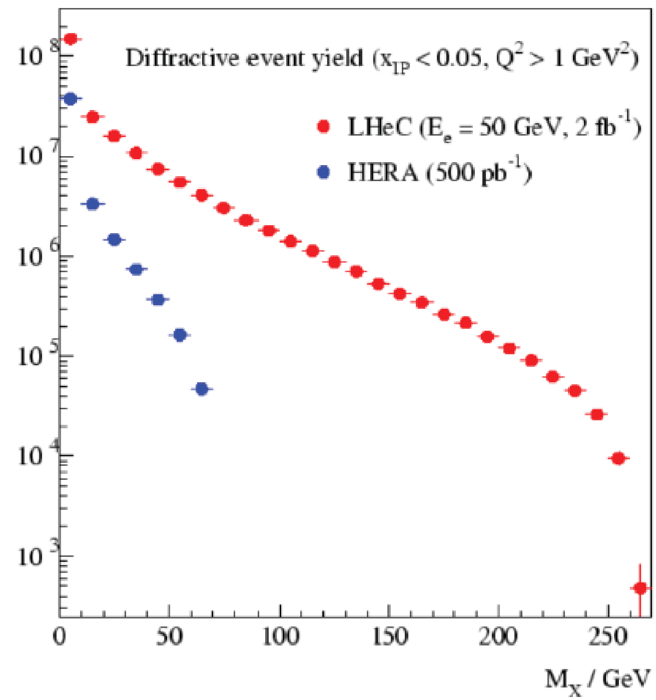
Diffraction at LHeC

Inclusive and exclusive diffraction can be studied at LHeC over a hugely expanded kinematical range, also using dedicated forward detectors

Compared to HERA significant extension of kinematic region of diffraction:
- → access to M_x up to 250 GeV
- → test collinear and proton vertex factorisation in significantly increased phase space domain
- → diffractive charged current
- → new diffractive channels: beauty, W/Z, new/exotic states (e.g. 1-- odderon) …





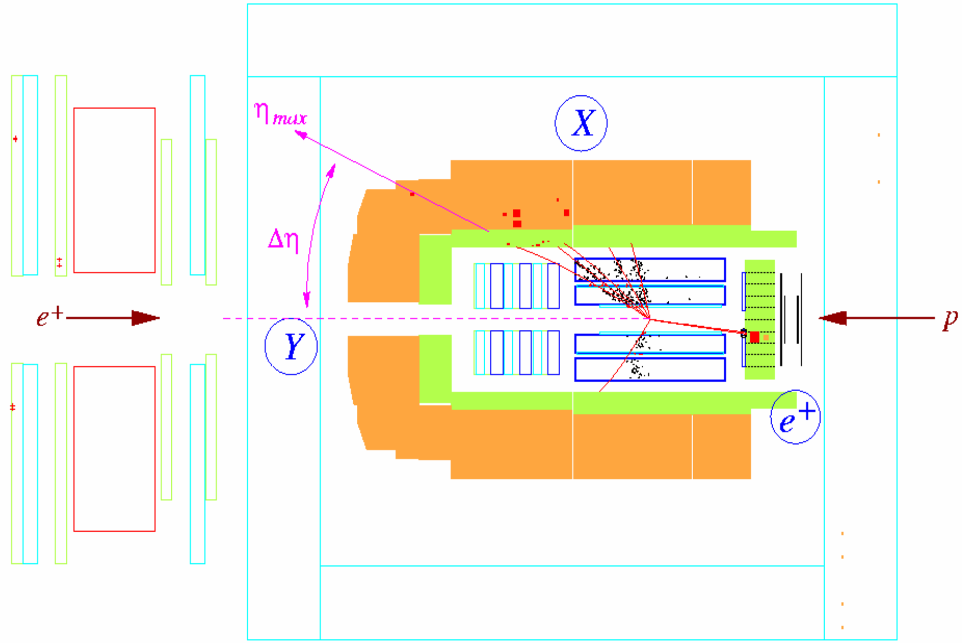


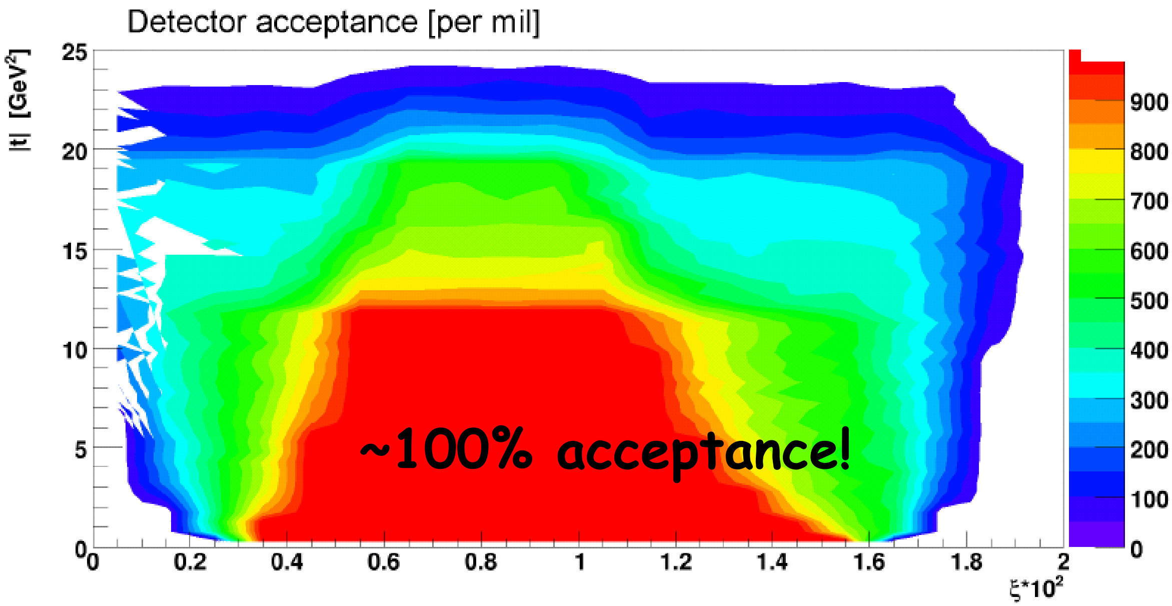
Diffractive event selection ($ep \to e'p'X$)

➢ 'Large Rapidity Gap' method (LRG)

- restricted to low x_{IP}
- exploit correlation between x_{IP} and η_{max}
- η_{max} <5 corresponds to x_{IP}~0.001 (require forward instrumentation down to 1^o)

- *t* is not measured
- may contain some p-diss. background
- syst.uncertainties due to missing proton





$$\xi \approx 1\text{-}E_{p'}/E_p \; (= x_{IP})$$

➢ 'Leading proton' measuremens

scattered proton detected in 'Roman Pots' (420m)

- *t* and x_{IP} measurement
- larger x_{IP} accessable
- free of p-diss. background
- overlap region with LRG method for cross-check

Diffractive event selection

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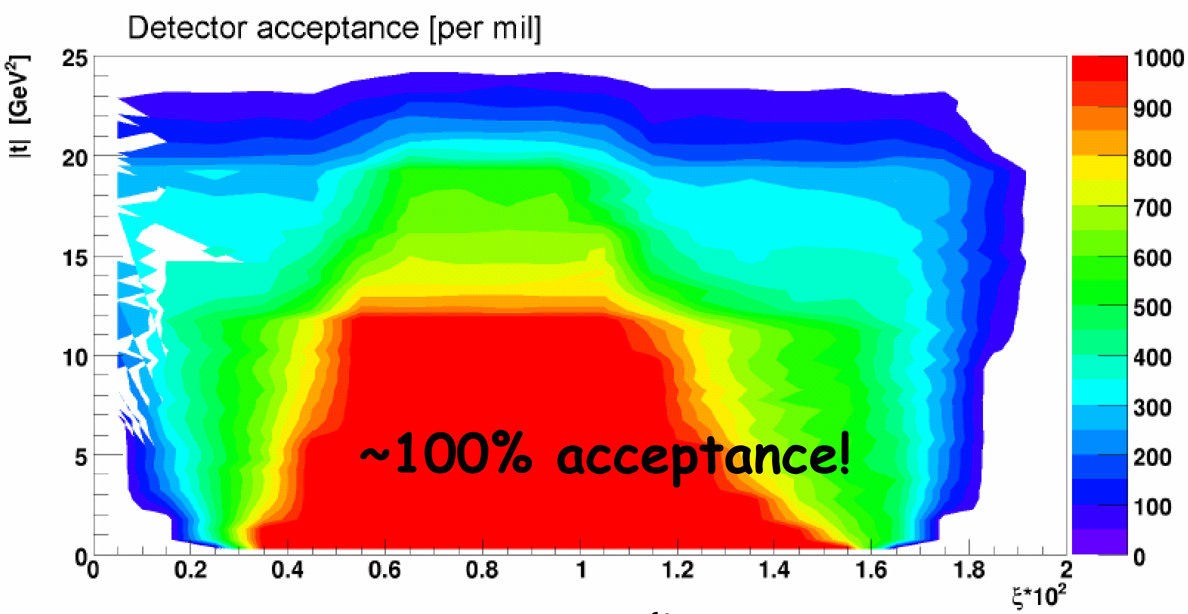
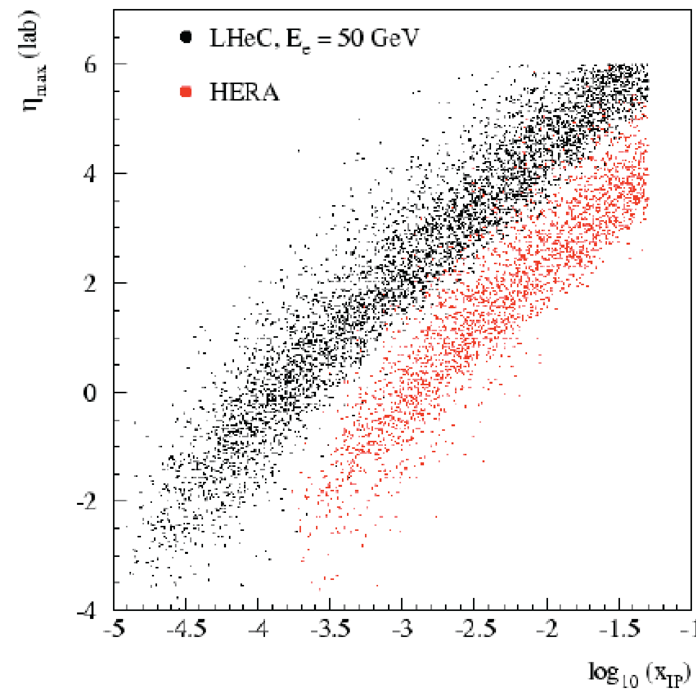


$\xi \approx 1 - E_p'/E_p$ ($= x_{IP}$)

η_{max} from LRG selection ...



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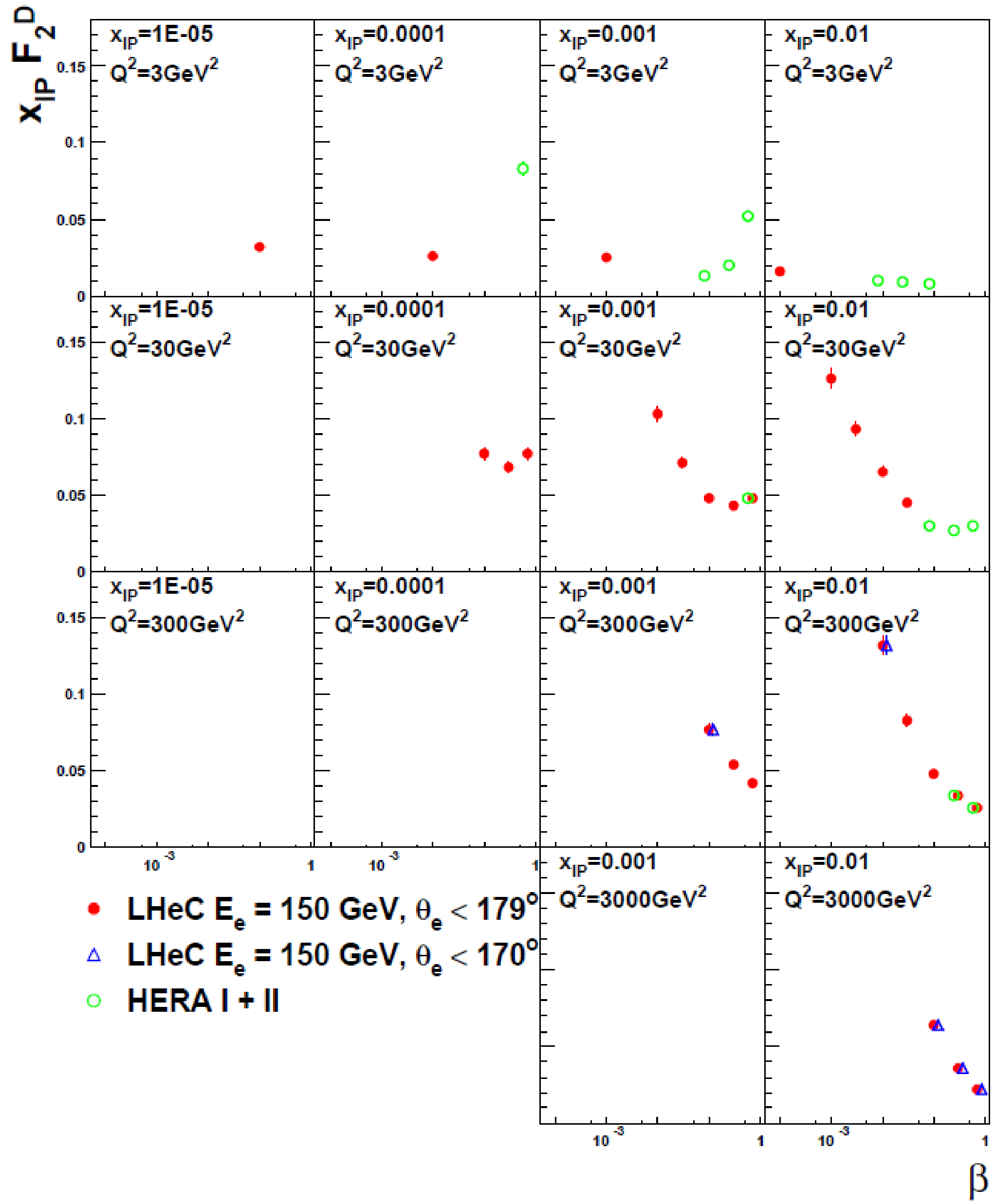
Diffractive F_2^D measurements

LHeC pseudodata

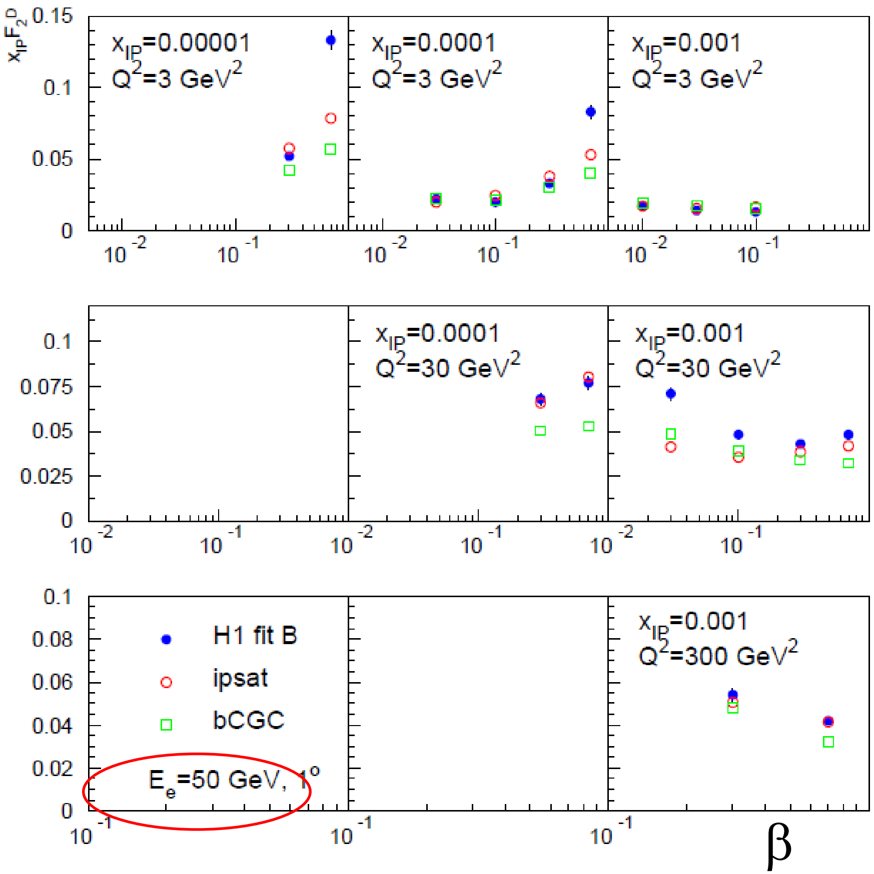
- Ee = 150 GeV, L = 2 fb^{-1}
- Extrapolation from "H1 fit B"

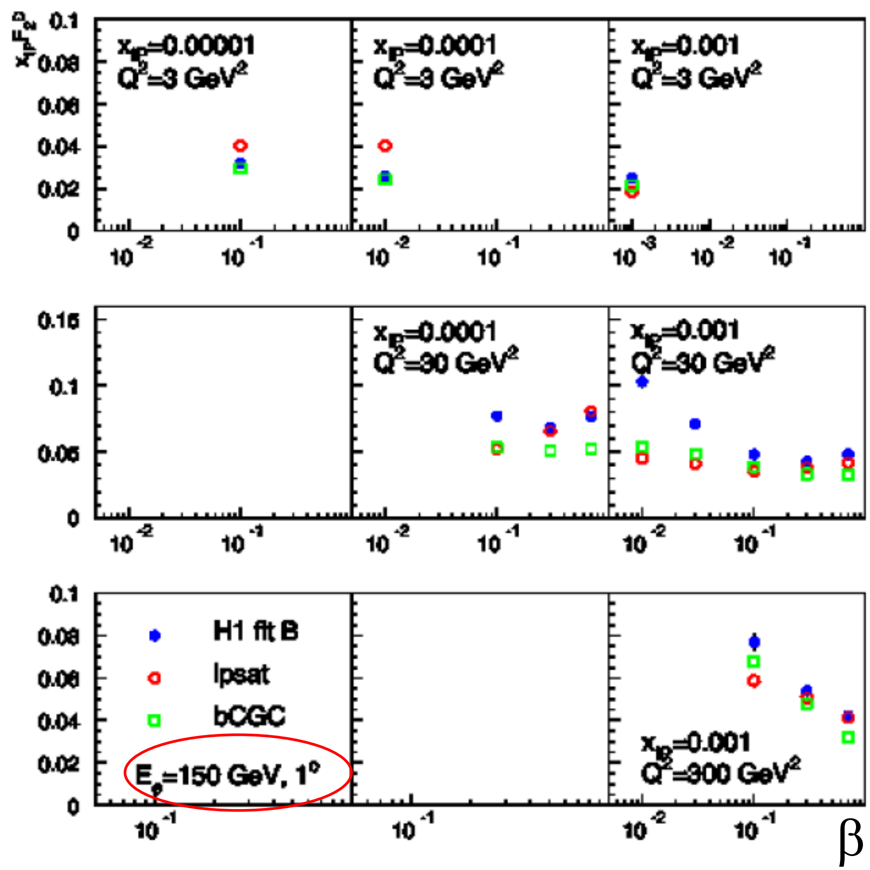
→ Large extension of HERA measurements!



Dipole models show differences w.r.t. linear-based extrapolations from HERA DPDF's and among each other: possibility to check saturation and its realization

- Diffractive DIS sensitive to power corrections of order Q^2_{sat}/Q^2
- LHeC gives access to semi-hard regime $Q^2 < 10$ GeV² and low x; can distinguish between a range of models with and without saturation effects



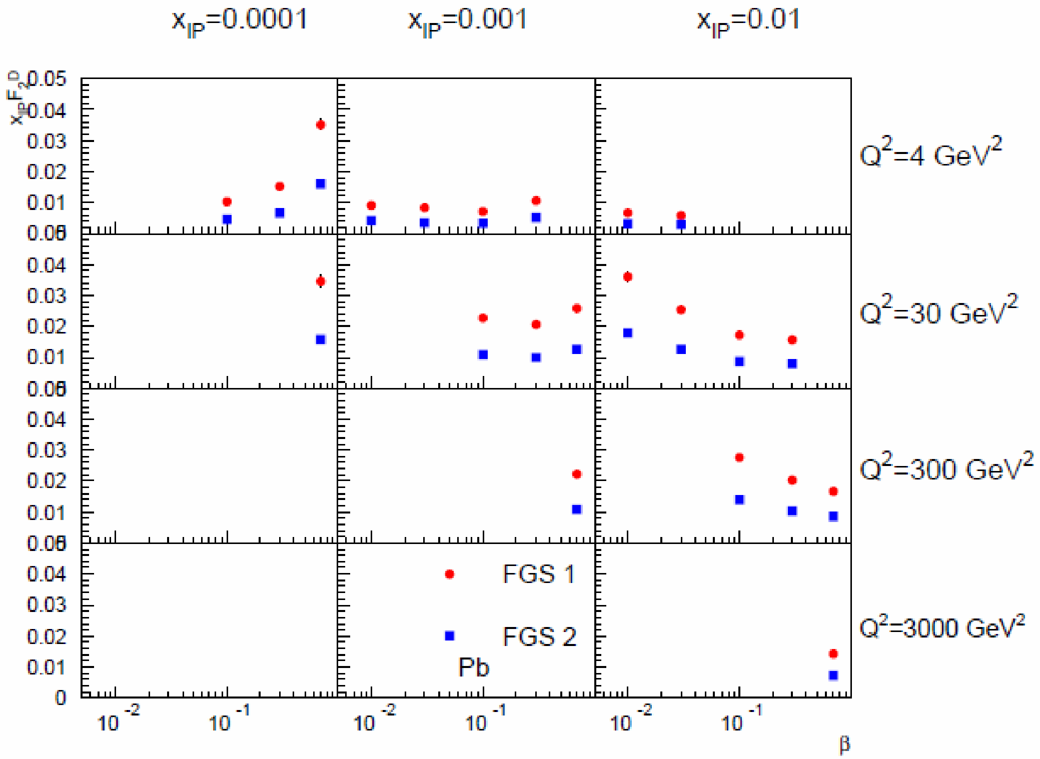


Diffractive DIS on nuclear targets

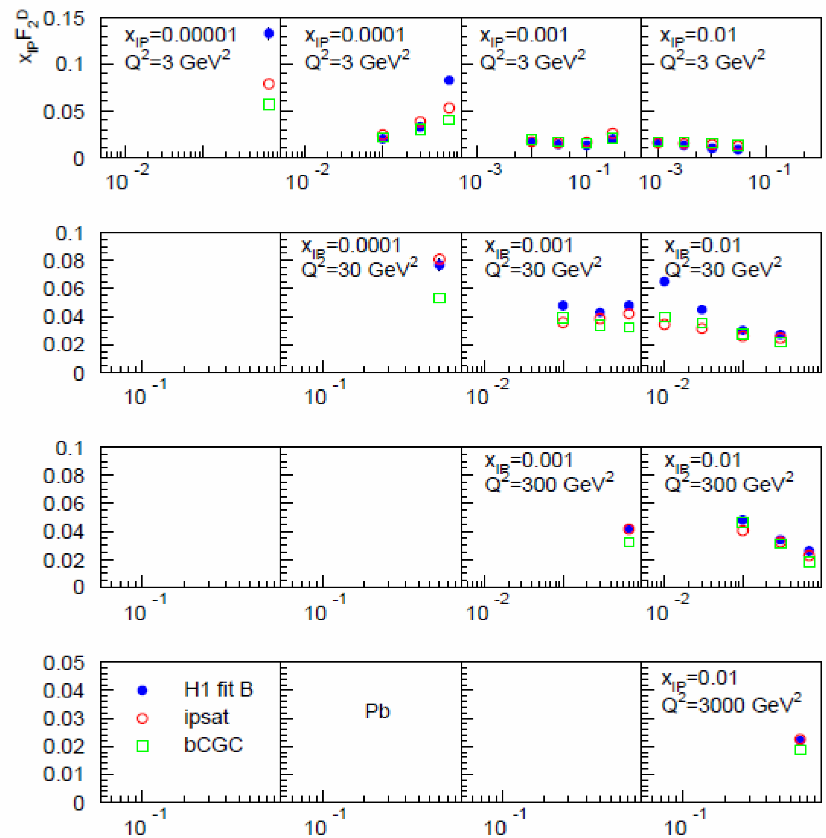
to be studied in eA at LHeC:

- if collinear factorisation (proved for proton) holds for nuclei
- Hadron vertex factorisation
- Diffraction is linked to nuclear shadowing: search for new effects

large differences between predictions for nuclear coherent diffraction

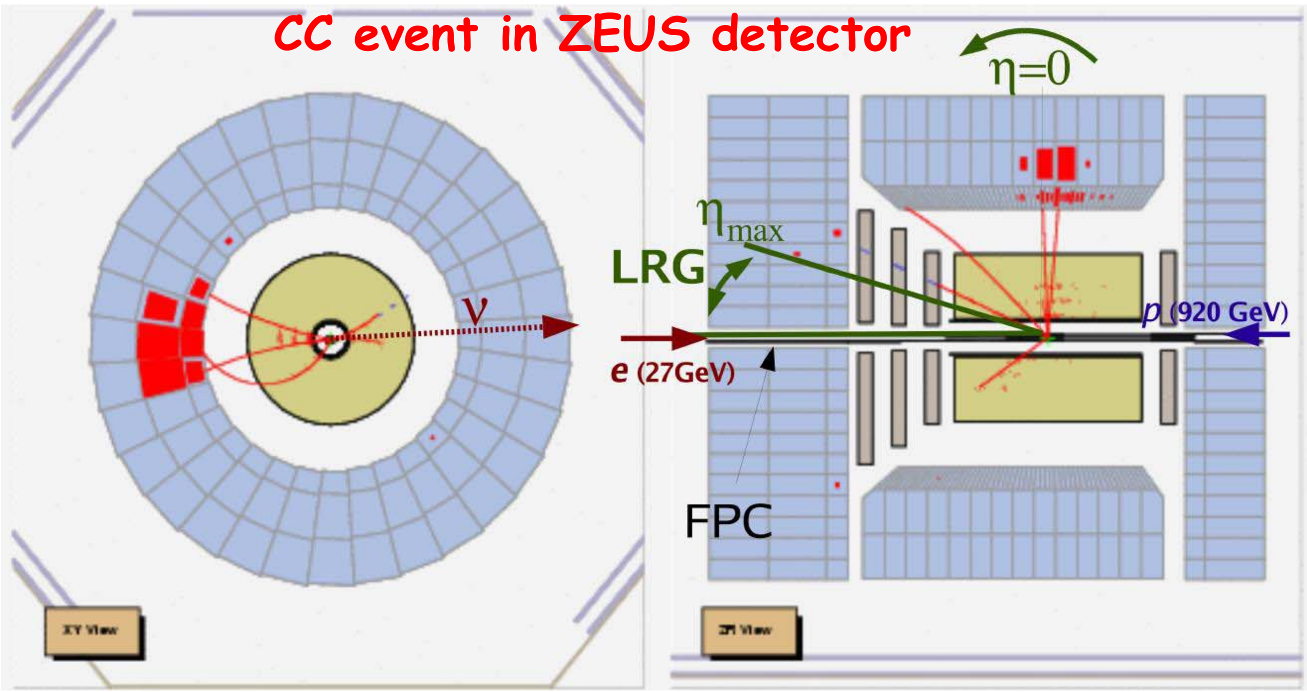


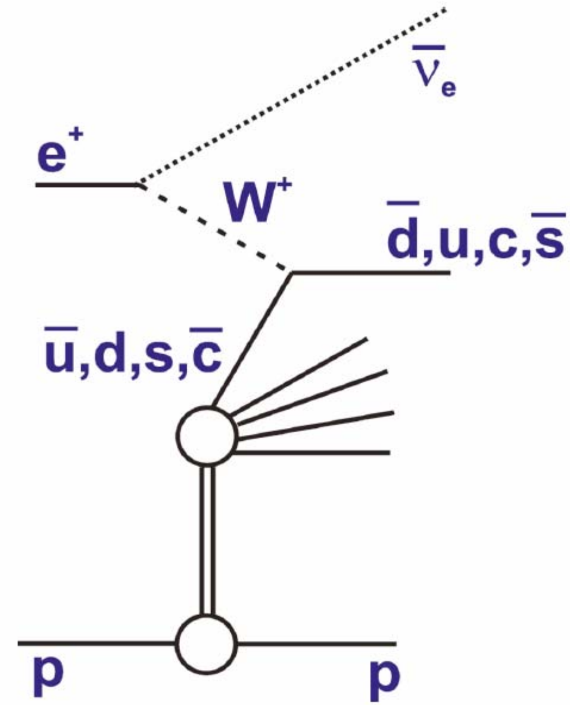
Frankfurt, Guzey, Strikman



Kowalski,Lappi,Marquet,Venugopalan β

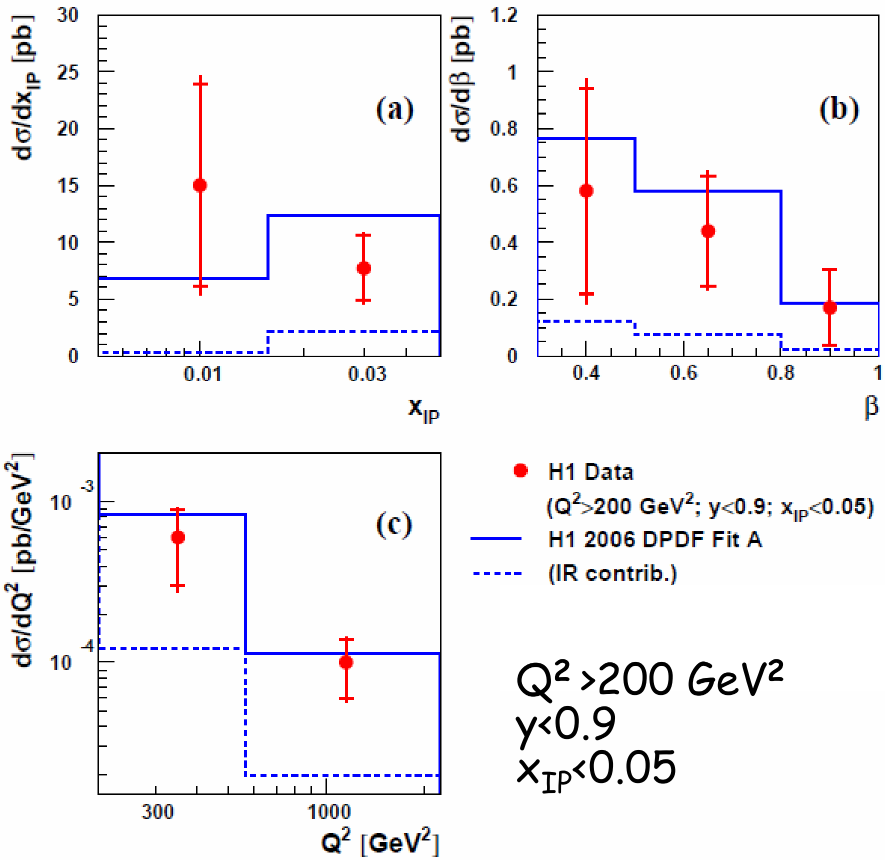
Sensitive to flavour decomposition of quark singlet (unconstrained by NC data)





H1: $\sigma^{CC,diff}$=0.39±0.12(stat.)±0.07(sys.) pb

ZEUS: $\sigma^{CC,diff}$=0.49±0.20(stat.)±0.13(sys.) pb



Q^2 >200 GeV^2
y<0.9
x_{IP}<0.05

Predictions for LHEC (RAPGAP MC)

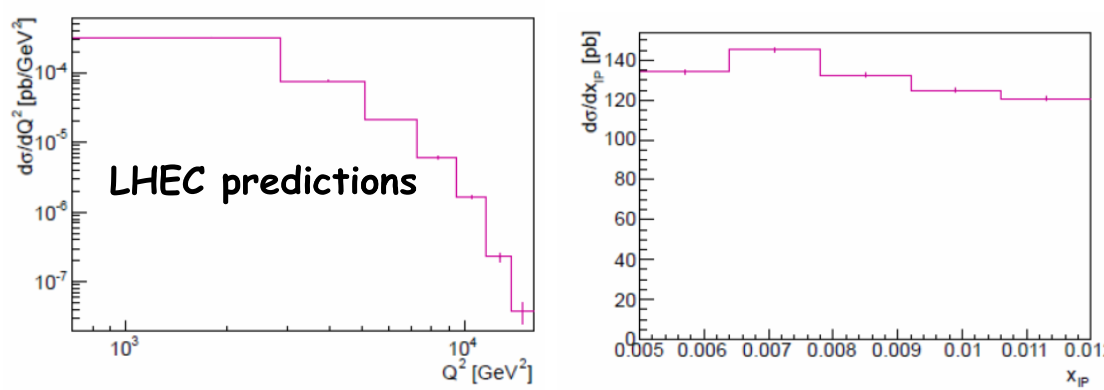
(Markéta Jansová, Bachelor work, Prague 2013)

Ep=7000 GeV, Ee=60 GeV

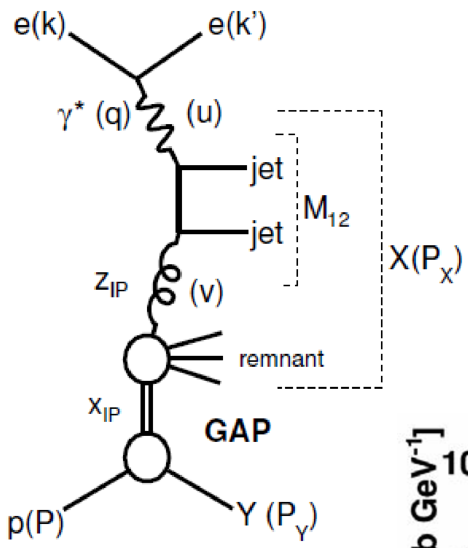
Q^2 >700 GeV^2, 0.2<y<0.9
0.005<x_{IP}<0.012

$\sigma^{CC,diff}$(MC)= 923 fb
~80,000 events (100 fb^{-1})

Sufficient statistics for detailed studies



Diffractive dijet production in DIS

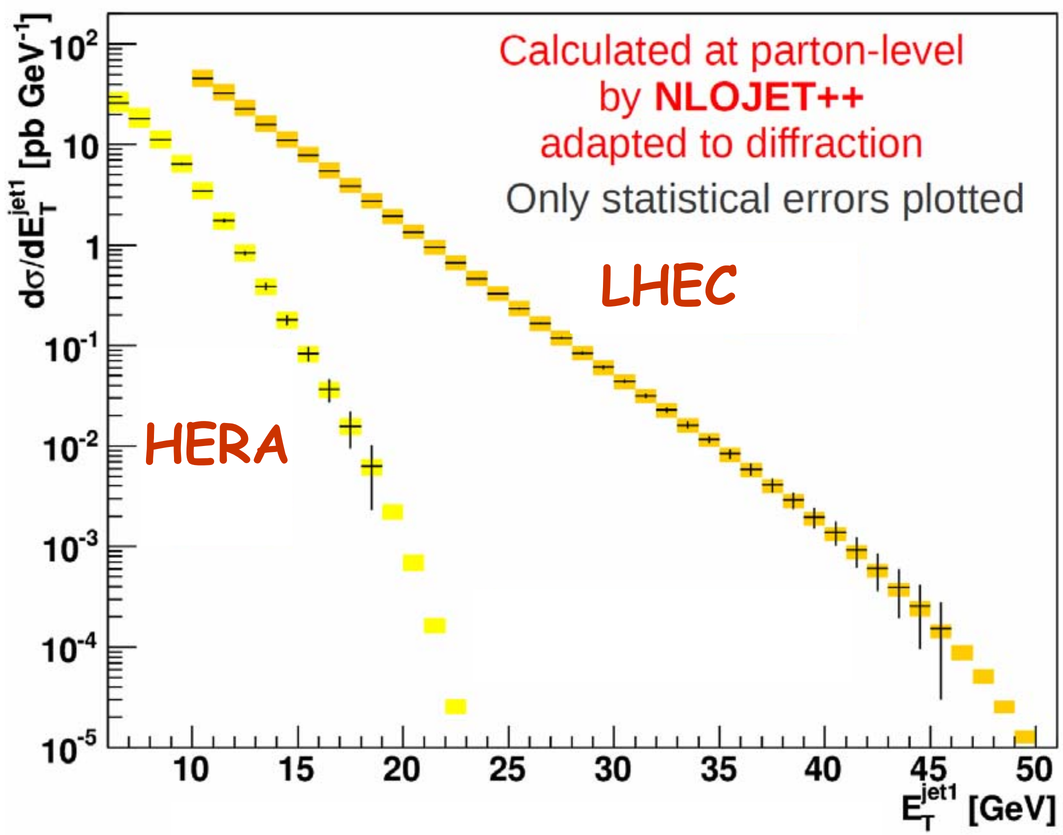


- Diffractive dijet and open heavy flavour production offer large possibilities for:

→ Checking factorization in hard diffraction.

→ Constraining DPDFs.

- LHeC→ Large yields up to large p_T^{jet}



920 + 27.5 HERA ($400\,\mathrm{pb}^{-1}$)

$Q^2 > 4\,\mathrm{GeV}^2 \wedge 0.1 < y < 0.7$

$x_{IP} < 0.03 \wedge |t| < 1\,\mathrm{GeV}^2$

$M_Y < 1.6\,\mathrm{GeV}$

$E_T^{jet1} > 6\,\mathrm{GeV}$

$E_T^{jet2} > 4\,\mathrm{GeV}$

$-1 < \eta^{jets} < 2$

7000 + 60 LHeC ($10\,\mathrm{fb}^{-1}$)

$Q^2 > 2\,\mathrm{GeV}^2 \wedge 0.1 < y < 0.7$

$x_{IP} < 0.01 \wedge |t| < 1\,\mathrm{GeV}^2$

$M_Y < 1.6\,\mathrm{GeV}$

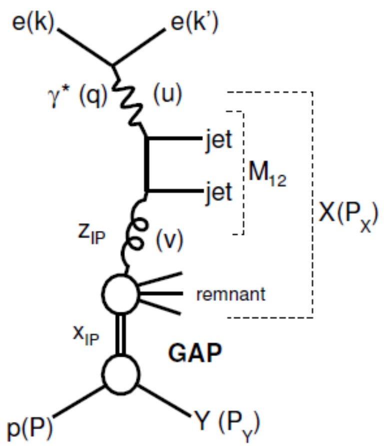
$E_T^{jet1} > 10\,\mathrm{GeV}$

$E_T^{jet2} > 6.5\,\mathrm{GeV}$

$-3 < \eta^{jets} < 3$

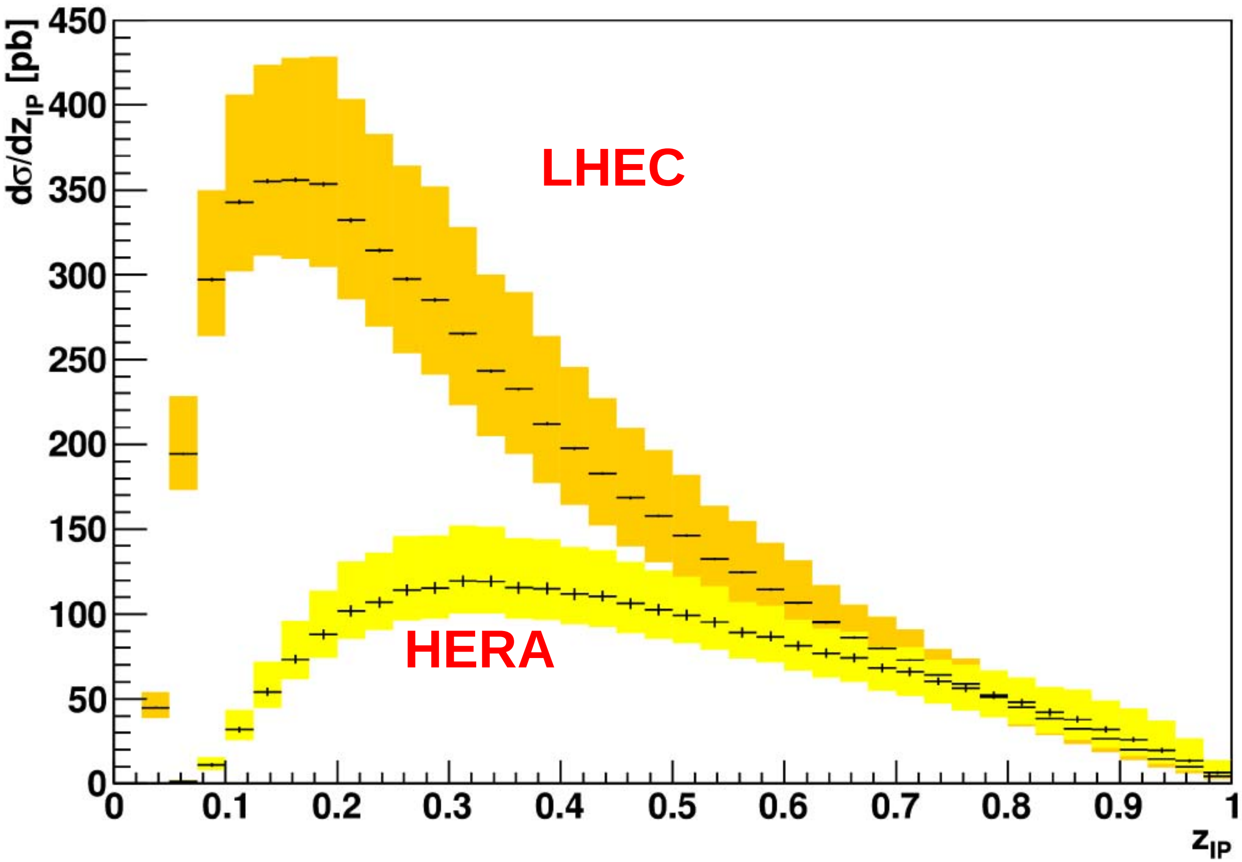
Diffractive dijet production in DIS

At LHeC cross-section dominates for small z_{IP}, where gluon part of DPDF dominates (weakly constrained from inclusive measurement)



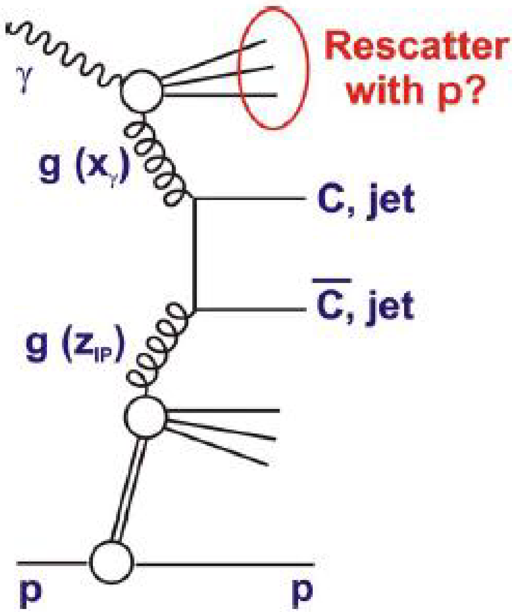
At LHeC smaller z_{IP} is accessed
z_{IP}~0.07 at HERA ;
z_{IP}~0.02 at LHeC

$$z_{IP}^{min} \simeq \frac{\left(E_T^{jet1(min)} + E_T^{jet1(min)}\right)^2}{x_{IP}^{max}\, y^{max}\, s}$$



analysis by Radek Žlebčík

Diffractive dijet production in photoproduction



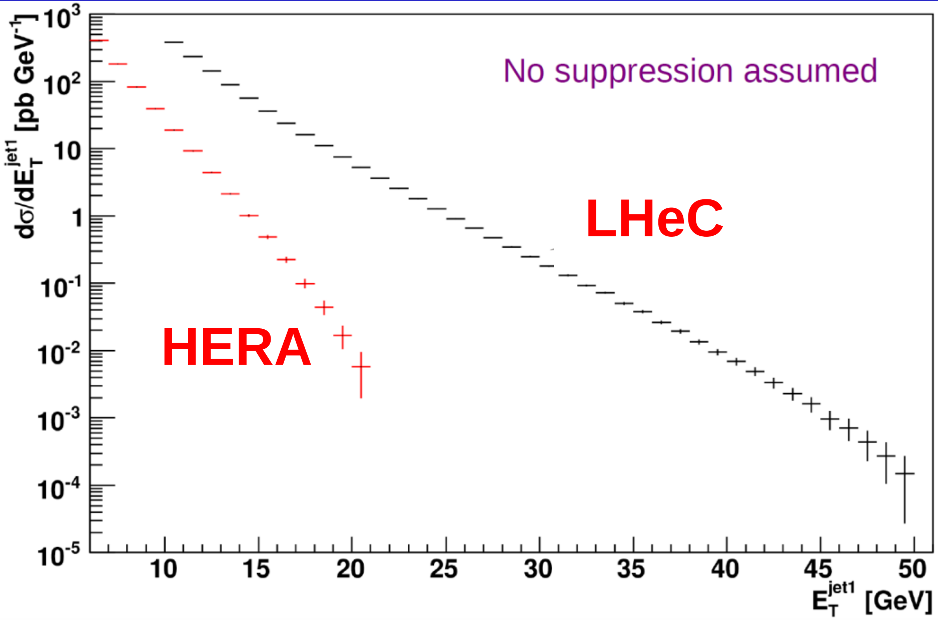
- Factorization in diffractive dijet photoproduction has been studied at HERA
→ controversial results, no clear conclusion

3 independent measurements by H1 obtained suppression factor
$S^2=\sigma(NLO)/\sigma(data) \sim 0.5\text{-}0.7$ (with large theoretical uncertainties),
ZEUS measurement consistent with **$S^2 \sim 1$**

- Theoretically predicted (e.g. KKMR group) dependence of S^2 on the fraction of photon's momentum in hard subprocess, $\mathbf{x_\gamma}$, not observed neither by H1 nor ZEUS.

- LHeC can clarify the issue with factorisation, survival probaility

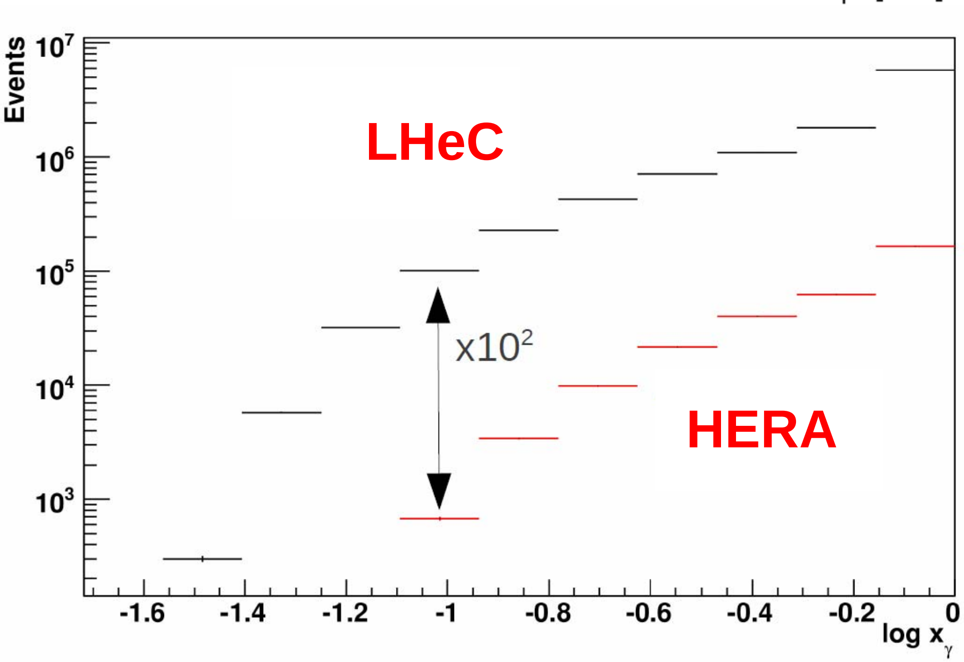
Diffractive dijet production in photoproduction



920 + 27.5 HERA (400 pb^{-1})
$Q^2 < 2\,GeV^2 \wedge 0.2 < y < 0.8$
$x_{IP} < 0.03 \wedge \vert t \vert < 1\,GeV^2$
$M_Y < 1.6\,GeV$
$E_T^{jet1} > 6\,GeV$
$E_T^{jet2} > 4\,GeV$
$-1 < \eta^{jets} < 2$

7000 + 60 LHeC (10 fb^{-1})
$Q^2 < 2\,GeV^2 \wedge 0.2 < y < 0.8$
$x_{IP} < 0.01 \wedge \vert t \vert < 1\,GeV^2$
$M_Y < 1.6\,GeV$
$E_T^{jet1} > 10\,GeV$
$E_T^{jet2} > 6.5\,GeV$
$-3 < \eta^{jets} < 3$

11

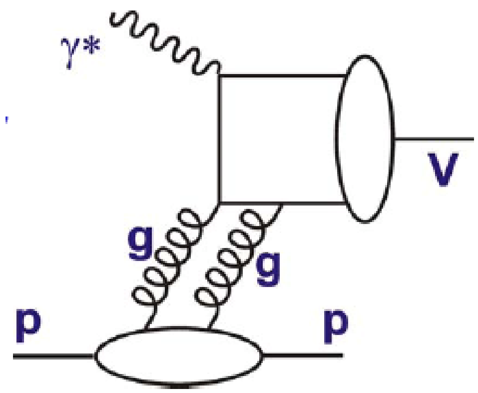


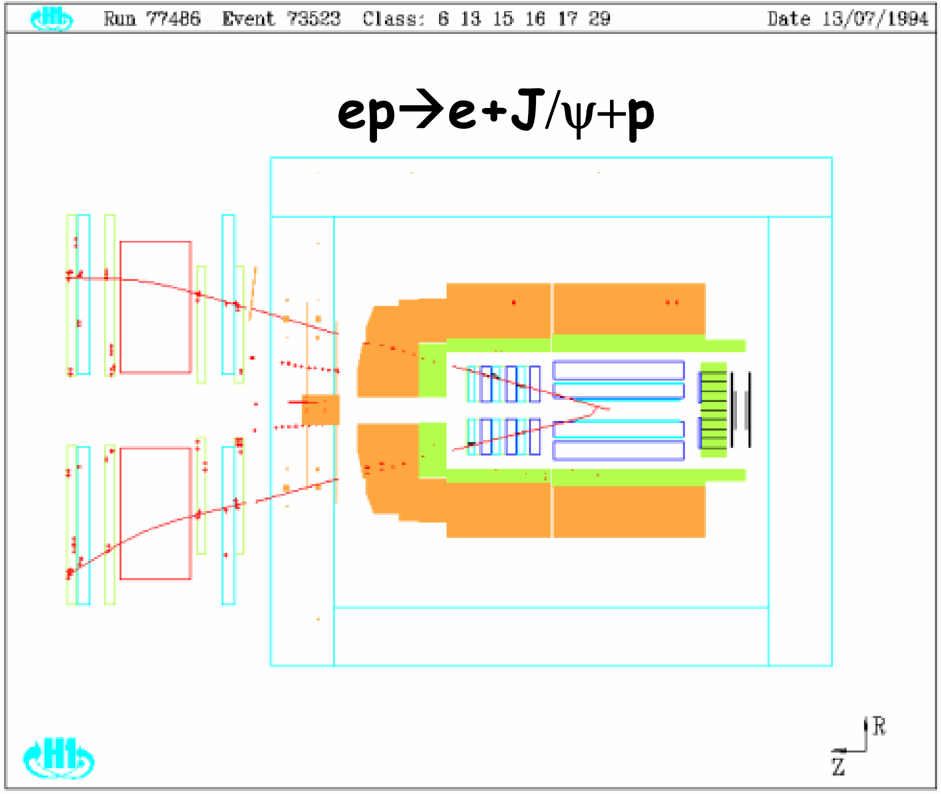
- Higher E_T of jets - smaller scale uncertainties in NLO QCD calc.
- Access to lower values of z_{IP} and x_γ than at HERA

E_T^{jet} ~ 17 GeV at HERA ;
E_T^{jet} ~ 42 GeV at LHeC

X_γ ~ 0.09 at HERA;
X_γ ~ 0.03 at LHeC

Exclusive Vector Mesons production (ep → e+VM+p)

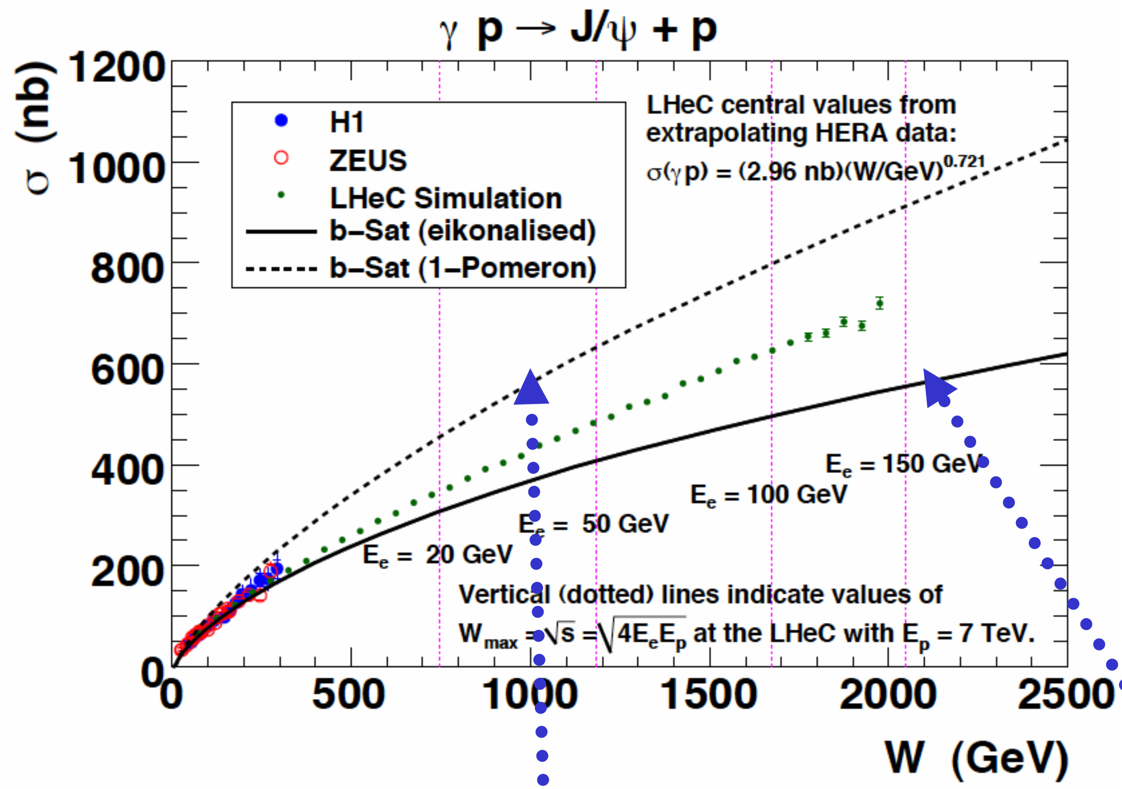




- Clean experimental signature

- Sensitivity to low x gluon up to $x_g \sim 6 \cdot 10^{-6}$ at $Q^2 \sim 3$ GeV^2

Elastic J/ψ production



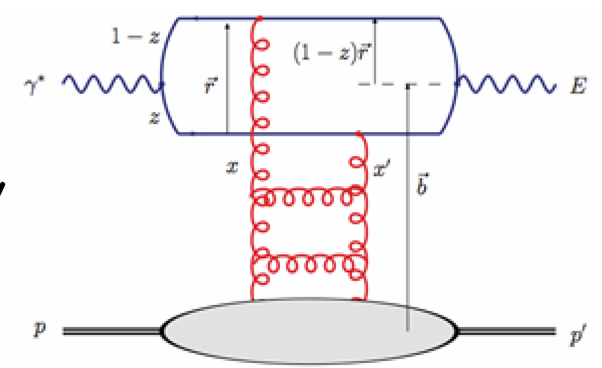
Simulated data from extrapolated fit to HERA data

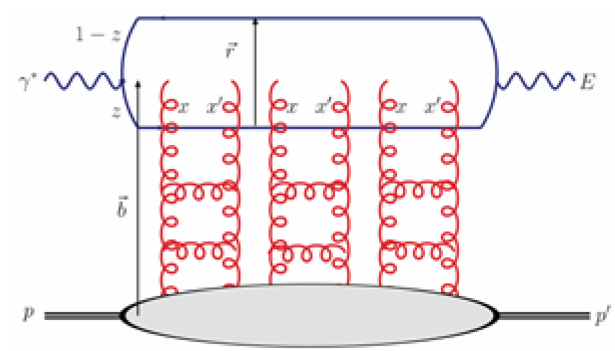
- Elastic J/ψ production sensitive to saturation effects

b-Sat dipole model eikonalised
- with saturation,
1-Pomeron - without saturation

LHeC can distuingish between the different scenarios

Linear, sensitivity to $(xg)^2$

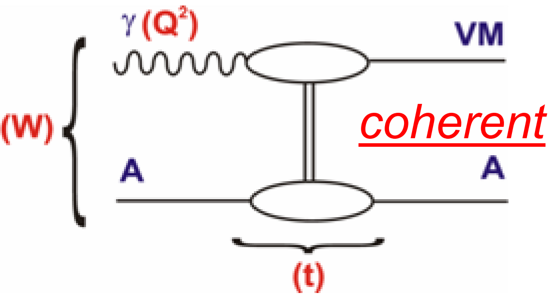


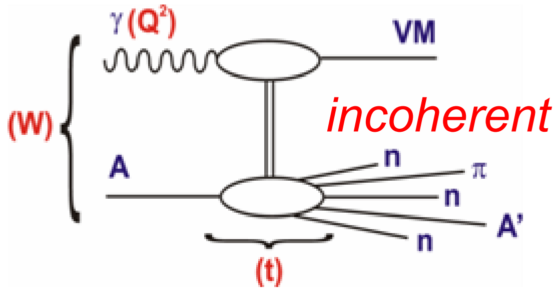


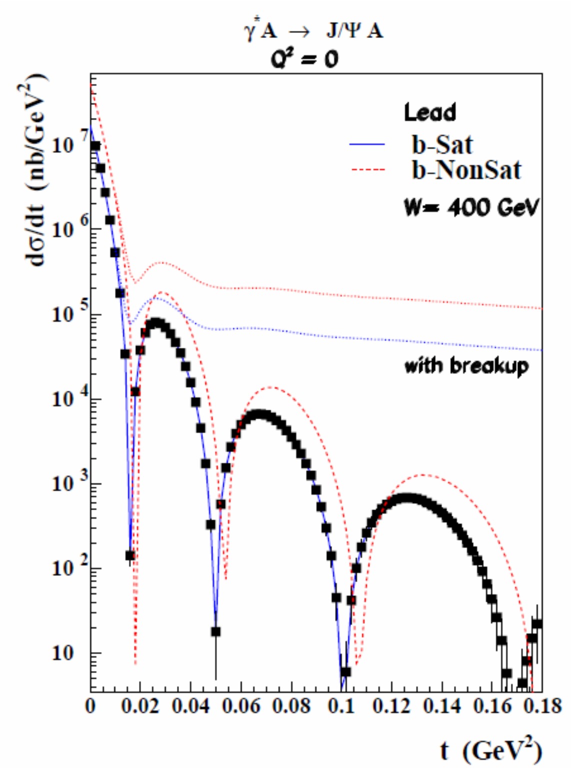
Non-linear, saturation

Elastic VM production off nuclei

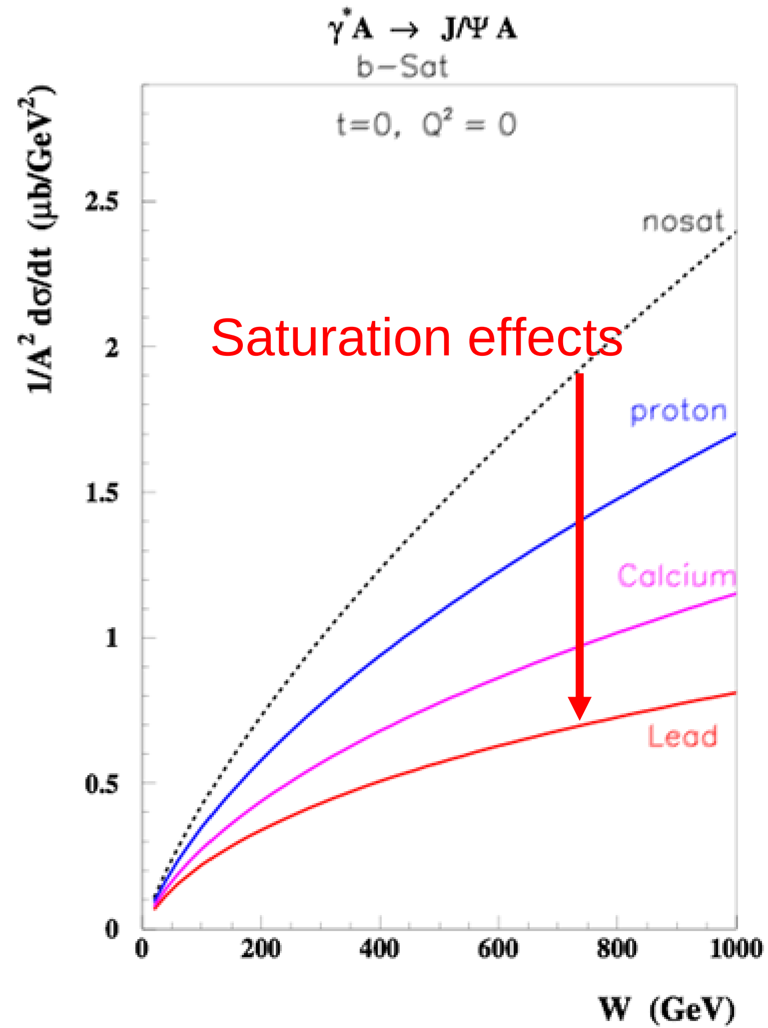
- Directly sensitive to gluon in nucleus;
- *t*-differential measurements give gluon transverse mapping of the hadron/nucleus





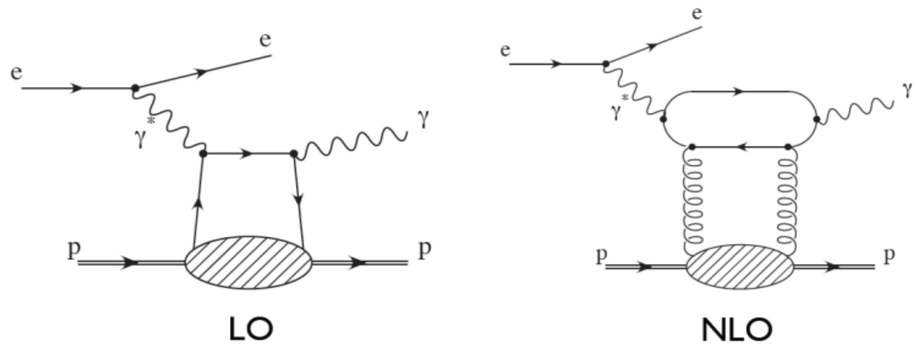


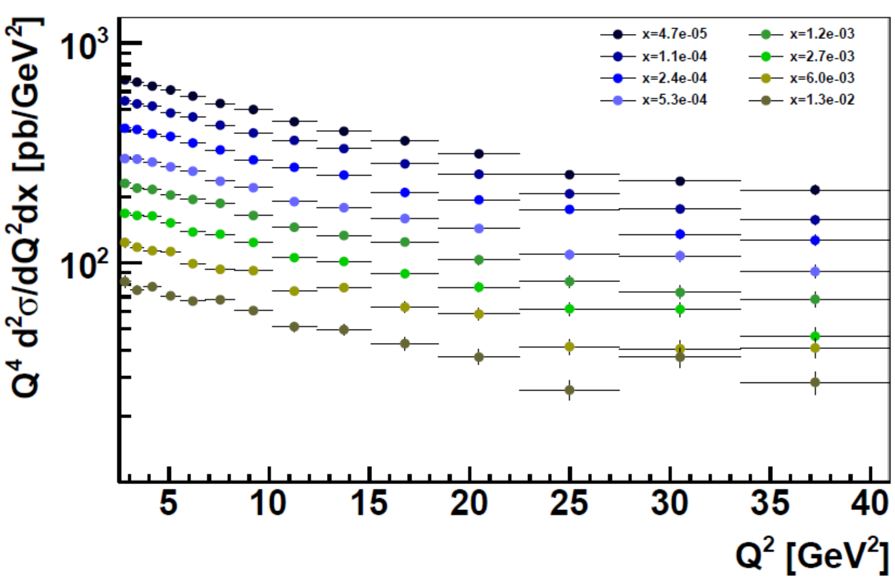
Challenging experimental problem: resolving the difference between models requires good separation of coherent and nuclear break-up



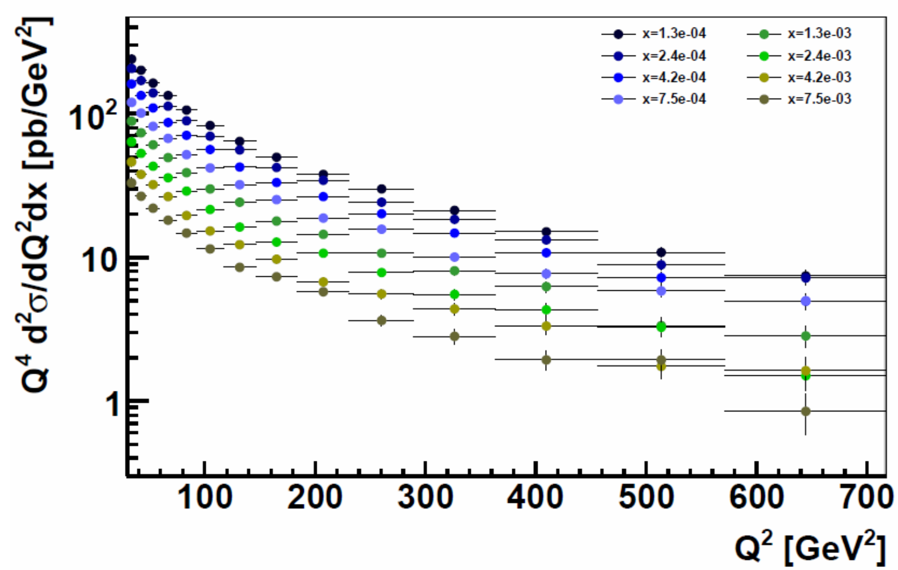
Deeply Virtual Compton Scattering ep→ eγp

- Exclusive processes give access to Generalized Parton Densities
- DVCS sensitive to the singlet quark GPDs
- Sensitive to dynamics / non-linear effects
- No complications due to meson wave function





L =1 fb^{-1} θ=1° P_T^{γ}=2 GeV
2.5 < Q^2 < 40 GeV^2

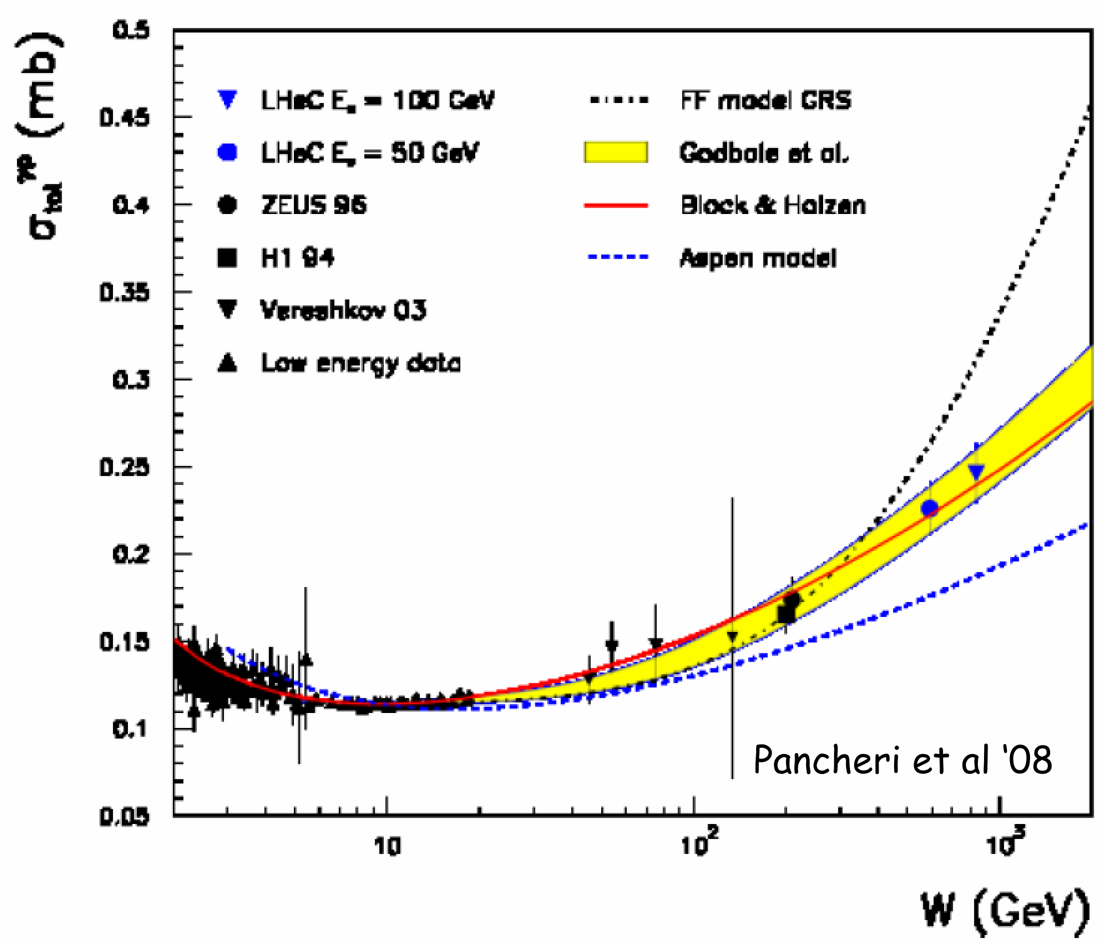


L =100 fb^{-1} θ=10° P_T^{γ}=5 GeV
50 < Q^2 < 500 GeV^2

Total photoproduction cross section

Small angle electron detector 62 m far from the interaction point:
$Q^2 < 0.01\ GeV^2$, $y \sim 0.3 \Rightarrow W \sim 650 \div 950$ GeV

- Substantial enlarging of the lever arm in W



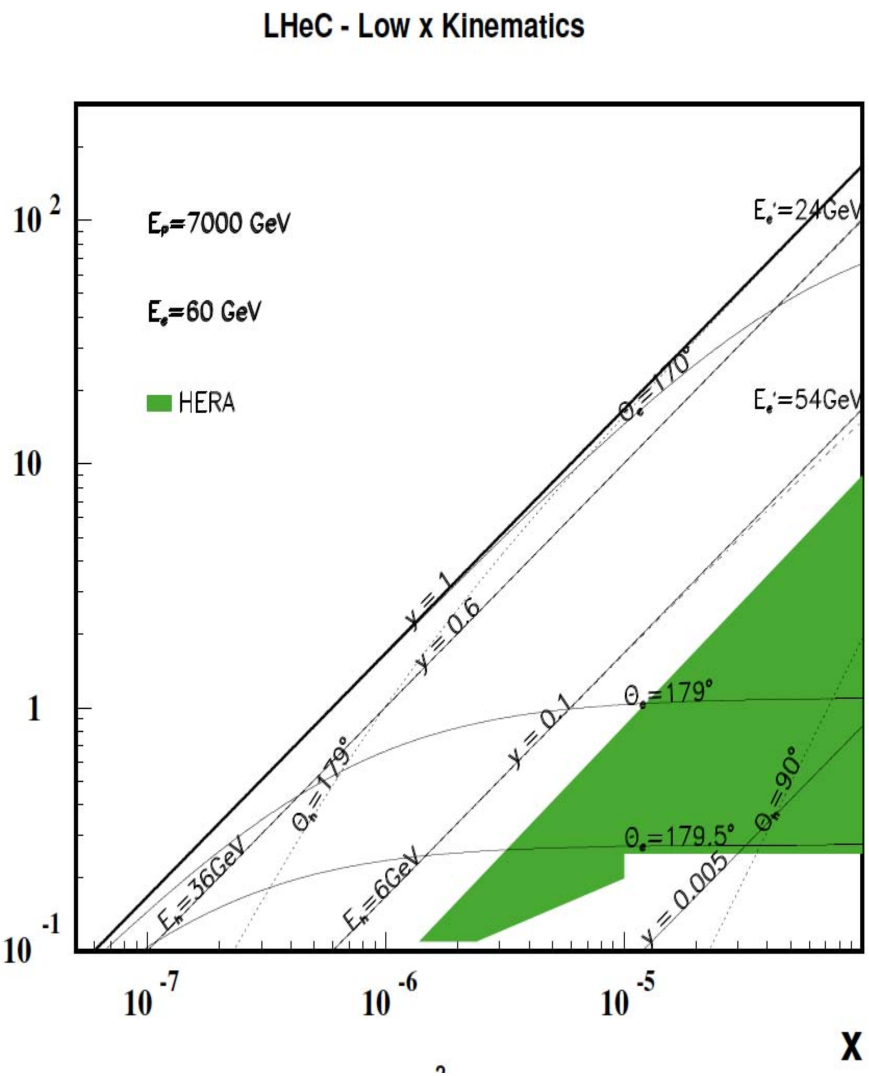
Summary

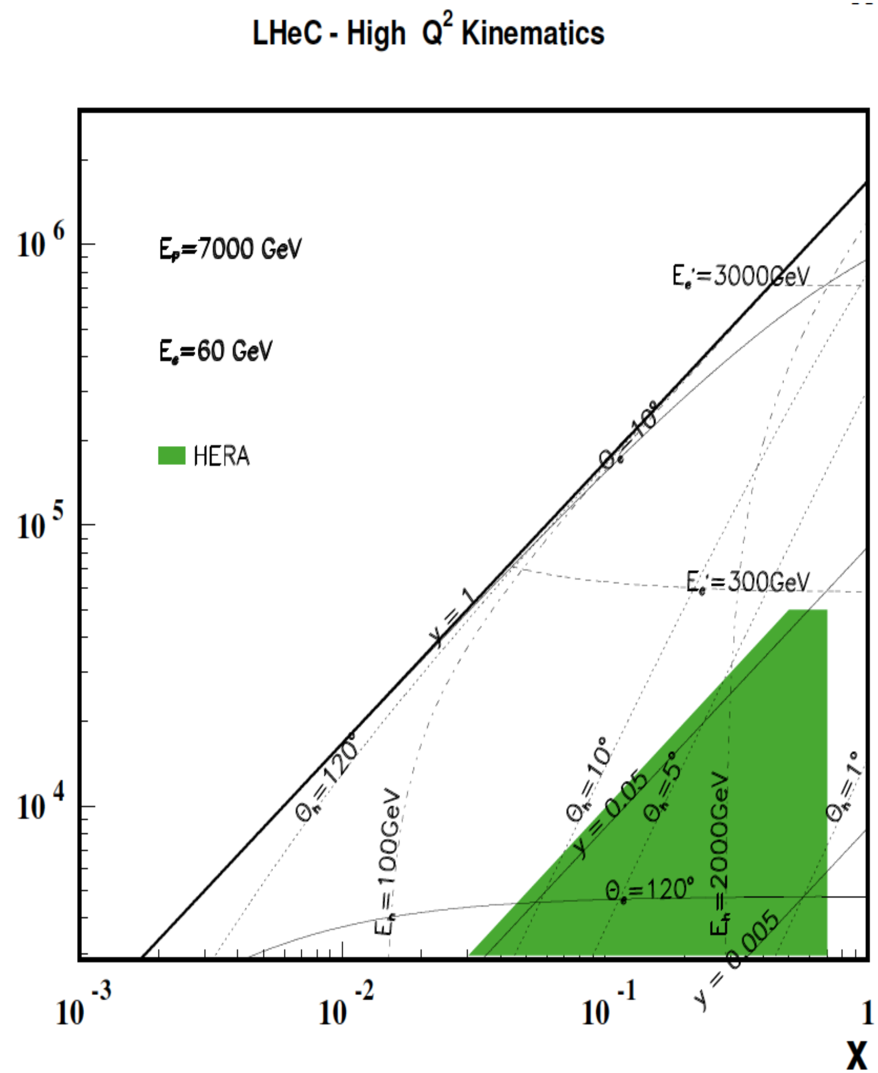
- the LHeC represents a natural extension to HERA and LHC
- unprecedented access to small x in proton and nuclei
- novel sensitivity to physics beyond standard pQCD
  → access to regime of saturation/ non-linear dynamics
- high-precision tests of collinear factorisation and determination of PDFs
- diffraction: access to high masses of diffractive system M_X, larger scales, E_t^{jets}
  → possibility for detailed studies of Charged Current diffractive interaction, factorisation in diffractive photoproduction, etc.
- possibility to study diffractive DIS on nuclear target
- and a lot more…

LHeC CDR, arXiv:2306.2913, 1211.4831, 1211.5102
http://cern.ch/lhec

backup

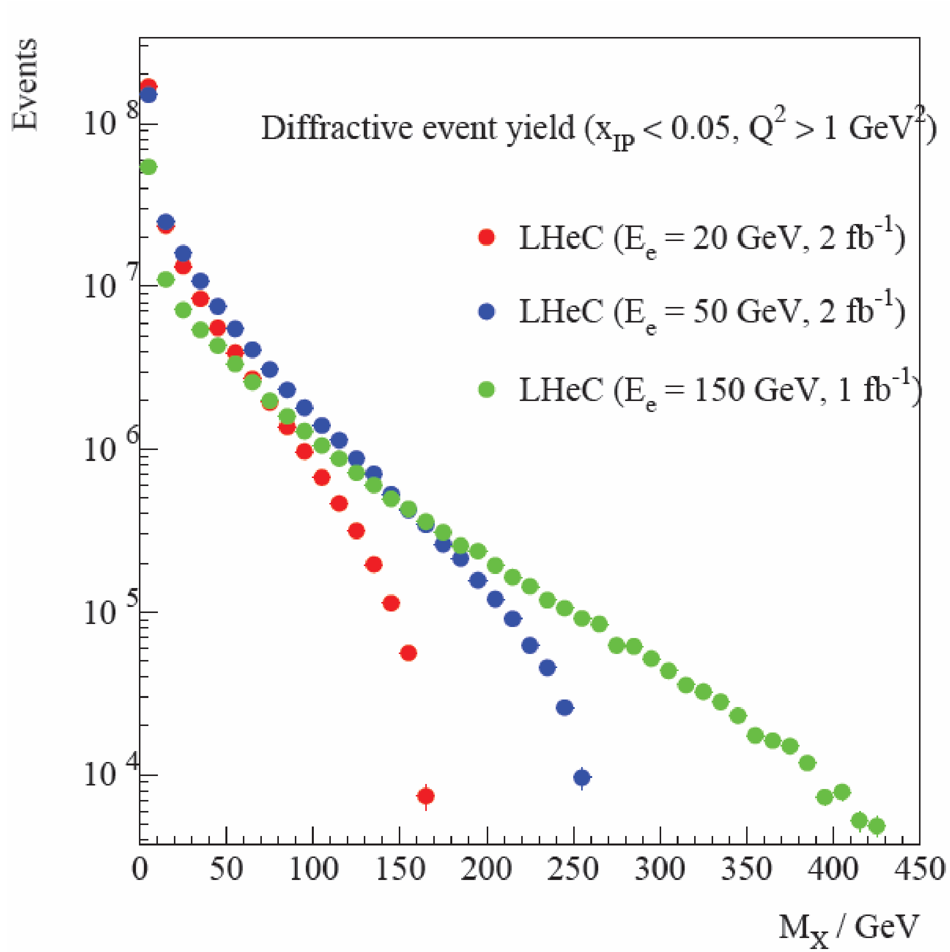
Kinematics


LHeC - Low x Kinematics
E_p=7000 GeV
E_e=60 GeV
HERA
E_e'=24GeV
E_e'=54GeV
Θ_e=170°
y = 1
y = 0.6
y = 0.1
y = 0.005
Θ_e=179°
Θ_e=179.5°
Θ_h=179°
Θ_h=90°
E_h=36GeV
E_h=6GeV
10^{2}
10
1
10^{-1}
10^{-7}
10^{-6}
10^{-5}
x

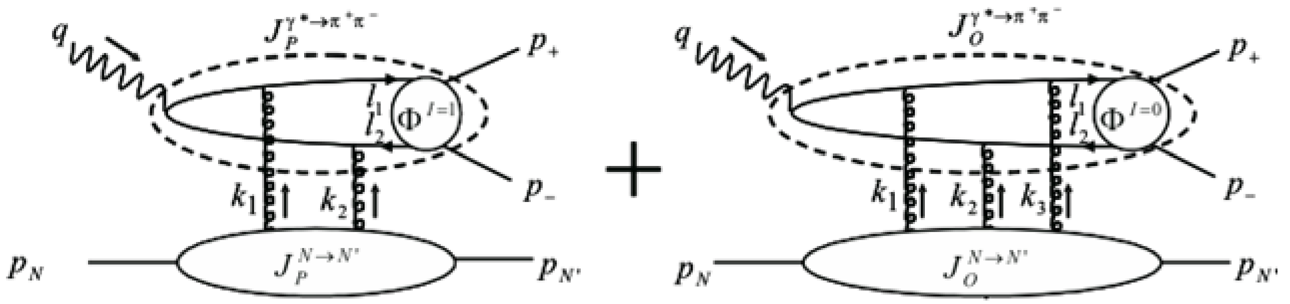

LHeC - High Q^2 Kinematics
E_p=7000 GeV
E_e=60 GeV
HERA
E_e'=3000GeV
E_e'=300GeV
Θ_e=10°
Θ_e=120°
y = 1
y = 0.05
y = 0.005
Θ_h=120°
Θ_h=10°
Θ_h=5°
Θ_h=1°
E_h=100GeV
E_h=2000GeV
10^{6}
10^{5}
10^{4}
10^{-3}
10^{-2}
10^{-1}
1
x

Diffraction and low x

- At LHeC, M_X up to hundreds of GeV can be produced with low x_{IP}
- New diffractive channels …beauty, W/Z
- Measure exclusively produced new/exotic 1^{--} states (odderon?)
- **Diffractive charged currents**
- **Dijets in DIS and Photoproduction**
- **Elastic J/ψ photoproduction**
- **Deeply Virtual Compton Scattering**



- Odderon (C-odd exchange contributing to particle-antiparticle difference in cross section) searched in $\gamma^{(\star)}p \to Cp$, where $C = \pi^0, \eta, \eta', \eta_c \ldots$ or through O-P interferences



$$A(Q^2,t,m_{2\pi}^2) = \frac{\int \cos\theta \, d\sigma(W^2,Q^2,t,m_{2\pi}^2,\theta)}{\int d\sigma(W^2,Q^2,t,m_{2\pi}^2,\theta)} = \frac{\int_{-1}^{1} \cos\theta \, d\cos\theta \, 2 \, \mathrm{Re}\left[\mathcal{M}_P^{\gamma_L^*}(\mathcal{M}_O^{\gamma_L^*})^*\right]}{\int_{-1}^{1} d\cos\theta \left[|\mathcal{M}_P^{\gamma_L^*}|^2 + |\mathcal{M}_O^{\gamma_L^*}|^2\right]}$$

Expect sizable charge asymmetry